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A STUDY OF THE PHOTOMECHANICAL EFFECT IN SILICON

BY

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A

THESIS

Submitted to the faculty of the

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Approved by

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ABSTRACT

This paper presents the results of an experimental investigation into the photomechanical effect in silicon. The effect was found to be very similar to the electromechanical effect. In both cases the phenomena observed is the softening of a thin surface layer of the material when it is either illuminated or when a current is flowing through the material.

An anisotropy was observed in both the hardness and the photomechanical effect. Increasing temperatures tended to "wash out" the photomechanical effect. The surface hardness and the photomechanical effect were found to depend heavily on proper surface preparation of the samples, however little dependence was shown on the impurity concentration within the samples. It was definitely established that high surface temperatures were not the cause of the softening. Most interesting and important, it was found that the radiation responsible for the photomechanical effect has an energy that is very close to that necessary to excite electrons into acceptor or out of donor levels of the semiconductor.

ACKNOWLEDGEMENTS

It is the author's pleasant duty to express his thanks to those who have made possible the performance of the present investigation.

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I. INTRODUCTION

In general, it has been observed that an increase in temperature will produce a lowering of the hardness of most materials. It has been observed that in silicon the passage of an electrical current will also produce a lowering of the hardness. These effects are not independent in that an increase in the temperature tends to wash out the electrical softening effect. More recently it has been reported that an effect analogous to the electrical effect may be obtained by illuminating the sample with a suitable radiation (infrared wavelengths).

This effect is termed the photomechanical effect and is defined as the lowering in indentation hardness of a surface that is illuminated with an appropriate radiation while the indentation is being made.

The present investigation is conducted to confirm the existence of this optical effect and to gather data concerning its dependence on temperature, crystallography, impurity concentration, and experimental procedures. All experiments are carried out on extrinsic silicon single crystals.

It is envisioned that this work may help to establish the location of donor and acceptor states as being on or about dislocations. This would show the dependence of energy levels on physical properties and also show the dependence of physical properties on electronic states.

II. REVIEW OF LITERATURE

As early as 1957, Kuczynski and Hochman (1) published a paper describing the photomechanical effect in semiconductors. In their work germanium, silicon, and indium antimonide were tested. These experiments yielded maximum photomechanical effects of 55, 70, and 20 percent respectively. At this time, they stated that the effect was isotropic within the limit of the accuracy of the equipment. The paper indicated that the effect was definitely limited to a layer a few microns thick. In a few experiments the radiation from the twin 140 watt spot lamps or Hanovia SH mercury lamps was filtered in an attempt to find the wavelengths responsible for the softening. The data indicated that the radiation must be in the range of two to four microns wavelength or in another band shorter than 0.4 microns. In order to control sample heating, the authors applied a thin layer of transparent liquid.

In a later paper, Kuczynski and Hochman (2) describe apparent light induced plasticity in thin garmanium samples bent to fracture while illuminated. In these samples the density of dislocations increased by a factor of 10^3 to 10^4 times the normal density. This increase in dislocation density indicated that plastic flow had preceded fracture in the samples bent while illuminated. Similar samples fractured in darkness gave no indication of any plastic flow whatsoever.

A similar result was reported by Kikuchi and Saito (3) in 1959 using a similar bending type arrangement.

The first very thorough work to be published was due to Westbrook and Gilman (7). This article has become the standard reference for all those who have followed. Their work dealt primarily with the electromechanical effect. This effect is very similar to the photomechanical effect, the only difference being the substitution of either an electric current or electric potential for the illumination as the source of energy. While the experimental work is greatly simplified by the use of an electric current, no information on energy bands or threshold energies can be obtained.

Westbrook and Gilman performed a large series of experiments on germanium with the intent of ascertaining whether the phenomenon was restricted to a particular set of physical conditions. A total of seven major experiments were performed. These experiments were to ascertain the effect on the softening caused by surface preparation, crystallographic effects, temperature, charge carriers, sample geometry, applied voltage, and time. Each of these major experiments involved many minor ones. In all cases, the authors found that their results were reproducible within the limits of the apparatus.

Surface preparation was found to have a significant effect on results. Mechanical polishing alone produced erratic and high values of hardness. Chemical polishing reduced the hardness to a lower, constant, and reproducible value. After prolonged contact with the atmosphere, the hardness of the surface would gradually decrease, presumably because of surface oxidation. Re-etching the surface always returned the hardness to the original value. No experiments were run to find out if there were any discrepancies in the electromechanical effect caused by a given surface preparation.

A thorough determination of the effect of crystallography on the effect was made by varying the crystallographic direction in which the current flowed and the direction in which the indentation was made. The zero current determination revealed a definite anisotropy in the indentation hardness of germanium. The electromechanical effect, however, exhibited no such anisotropy, there being a quantitatively similar effect in all directions of flow of the electric current for indentations made in the same plane. In this case, the Knoop diamond indenter was used not only because of the shallow indentation, but also because the asymmetric rhombic shape enabled crystallographic anisotropies to become apparent.

A series of runs was made on an intrinsic germanium specimen from temperatures as low as -196°C up to +200°C. Subambient temperatures were maintained using liquid nitrogen and various ice baths. The temperatures above room temperature were obtained using a silicone oil bath and electric heaters. The hardness-temperature characteristic of the zero current series showed the typical brittle substance profile in that there is a slight decrease in hardness with increasing temperature. The hardness-temperature plot showed the curve of hardness observed while a current was flowing approaching the zero current hardness curve with increasing temperature. Low temperatures greatly enhanced the softening. The -196°C temperature produced electromechanical effects of over 50 percent.

Current density-hardness plots were prepared for intrinsic and both N and P type extrinsic germanium single crystals. It was found that increasing impurity concentrations, of both N and P varieties, increased the zero current hardness. Increasing current densities produced a very similar softening effect, the plots being almost parallel. Only in a few cases was there a discrepancy in this pattern. In these cases, a few N type germanium samples exhibited anomolously high initial softening which with increasing current density became parallel to the other plots. Purity levels ran from intrinsic to 10^{19} impurity atoms per cubic centimeter or equivalently, from zero to a hundred parts per million.

As electrode effects at times tend to confuse semiconductor experiments, the electromechanical effect was measured near each electrode and in the center of the sample. All three measurements yielded the same result.

Next Westbrook and Gilman varied the indenter load so an estimate of the depth to which the effect is operable could be made. They found that there was no softening when the depth of penetration was greater than two microns. This figure was checked using both Knoop and Vickers diamond indenters. Also, in order for the electromechanical effect to be made as large as practically possible for this experiment, it was performed at low temperatures.

It was found that there are certain time dependencies involved in the electromechanical effect. It was thought that there may have been some dependency on the indenter loading duration. However, this proved false. Next, different periods of loading were tried. The interval of loading was broken up into the initial period, when surface contact is made and just beyond; the middle period, where the indenter is in contact at the beginning and the end of the period: and the final period, in which the indenter is in contact and is raised. It was found that the period of loading during which the electric current was allowed to flow did drastically affect the softening. The experiments indicated that a larger effect was exhibited when the current is flowing at the beginning of the indentation, although there was an electromechanical effect shown when the current was allowed to flow only in the latter stages of loading.

Westbrook and Gilman's investigation was very thorough, however, only ten indentations were made in any one experimental geometry. Seeming inaccuracies in the points plotted for curves might be explained by noting the statistically small number of sample points.

No further American work has been found in the literature on the electromechanical or photomechanical effects. Chronologically, the next article was published in October, 1961, in Fizika Tverdogo Tela by M. S. Ablova (4). Ablova was concerned with the microstructure of microhardness indentations. He observed that visible bands parallel to the top edge of the indentations were being formed on the walls of microhardness indentations made in germanium samples. These bands were postulated to be slip lines. This property was not observed in any other system. The slip lines were said to result from the return to equilibrium conditions after the indenter was raised. Before raising the indenter, there are large elastic restoring forces present in the walls of the indentation. Releasing these forces allowed further plastic deformation and the slip lines resulted.

Gorid'ko, Kuz'menko, and Novikov (5) studied the photomechanical effect from the standpoint of changes in mechanical properties with changing current carrier concentration. They viewed the absorption of the infrared radiation as a convenient method of changing the current carrier density within the germanium samples they used. By surrounding the sample with six 300 watt projection lamps, the total illumination was brought to the order of 50,000 lumens per square meter. Besides using illumination as a source of current carriers, excess carriers were injected into the surface using tungsten point contacts. In this article, only hardness versus level of illumination and hardness versus applied potential relationships were discussed. The curves in both cases were the same. The method of introduction of excess carriers seemed to make little difference. Gorid'ko, et al, state that it is now reliably known that the change in surface properties is due to a change in current carrier concentration. Since measurements were performed on dislocation free (10^2 per cc) and on normal germanium with the same results, it was felt that the carrier concentration affected the mobility of the dislocations. The authors pictured the mechanism in N type semiconductors as being a "metallization" of covalent bonds near dislocations that have captured excess carriers. The carrier was supposed to make the bond more symmetrical and less saturated so that there is less resistance to glide. No mention was made of a mechanism for P type materials.

Gurevich, Lang, and Firsov (6) presented a theoretical paper in which the method of absorption of infrared radiation by free carriers of a semiconductor was considered. The case of the cubic crystal was investigated. Fermi and Boltzmann statistics yielded similar results. The absorption was found to depend on the frequency of the radiation and upon temperature.

Kuz'menko, Novikov, and Gorid'ko (8) found that the photomechanical effect was not limited to the classical semiconductors, germanium and silicon, but could also be found in antimony and bismuth. Effects of up to 45 percent were observed. The photomechanical characteristics were very similar to those of silicon and germanium. Experiments were also performed on very good conductors, as copper, with no photomechanical effect observed. It was postulated that any material with a fundamental absorption in the infrared would exhibit softening under illumination. Illumination of 50,000 lumens per square meter was obtained using 300 watt lamps. To keep heating to a minimum, the surface was wetted with alcohol and the sample itself was attached to a large block of copper. In this manner temperature increases were limited to two or three degrees centigrade. Experiments with filtered radiation yielded positive results only when infrared wavelengths were used.

Beilin and Vekilov (9) found that the plasticity of germanium samples increased greatly when the samples were stretched while illuminated. The experiments were performed on samples 0.1 millimeters thick. They also observed that there was no dependence on indenter load, i.e. there was no surface layer to which the effect was confined. It was these authors' belief that the effect was due to the decrease in charge on dislocations and the increase in conduction electrons. These two effects were said to have made the material behave more like a metal.

Sandulova and Rybak (10) have reported an anisotropy in the microhardness of silicon. It was observed that the (111) plane had the highest microhardness. However, the difference was diminished and was finally washed out by longer etching durations. The silicon single crystals used were grown from the gaseous state and indented without prior mechanical or chemical polishing. As noted, chemical polishing tended to remove the anisotropy.

Further work on the anisotropy of silicon by Ablova and Feoktistova (11) corroborated the findings of Sandulova and Rybak.

Additional work on the electromechanical effect in semiconductors has been performed by Ablova (12). This investigation was very similar to that of Westbrook and Gilman, although not nearly as thorough. One characteristic stood out from the rest of his data. It was reported that the electromechanical effect was only observable in samples that were freshly polished. The softening disappeared after a month of contact with the atmosphere. Ablova also noted a complete lack of softening for his purest samples. These had impurity concentrations of the order of $4\text{-}8 \times 10^{13}$ impurity atoms per cubic centimeter. Ablova also suggested that the photomechanical effect should exhibit similar characteristics.

III. EXPERIMENTAL PROCEDURE

A. Equipment

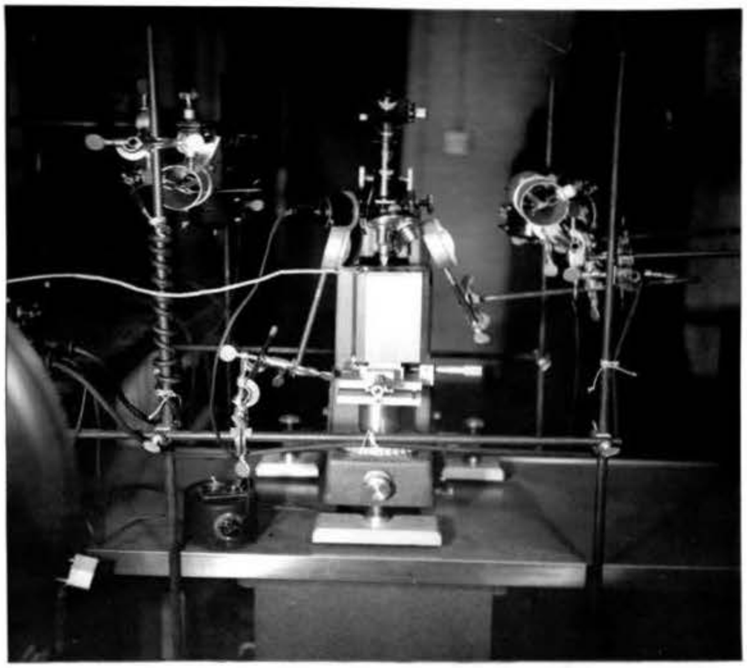
The experimental setup is shown in Figure I. The apparatus was built around a Kentron Micro Hardness Tester produced by Riehle Testing Machines. Tests may be conducted with indenter loads varying from one to one thousand grams. Since the effect in question was a surface effect and since silicon is very brittle and subject to severe cracking, only light loads, one to thirteen grams were used.

To decrease errors caused by excessive impact, the indenter was slowly lowered to the surface by an oil filled damping device. In these experiments, the damping device was adjusted to allow the indenter to make contact with the surface of the specimen ten seconds after the test was initiated. The indenter was retained in the raised position by means of a lever on the exterior of the test machine. Release of the catch holding the lever initiated the test. This lever is shown in Figure IV.

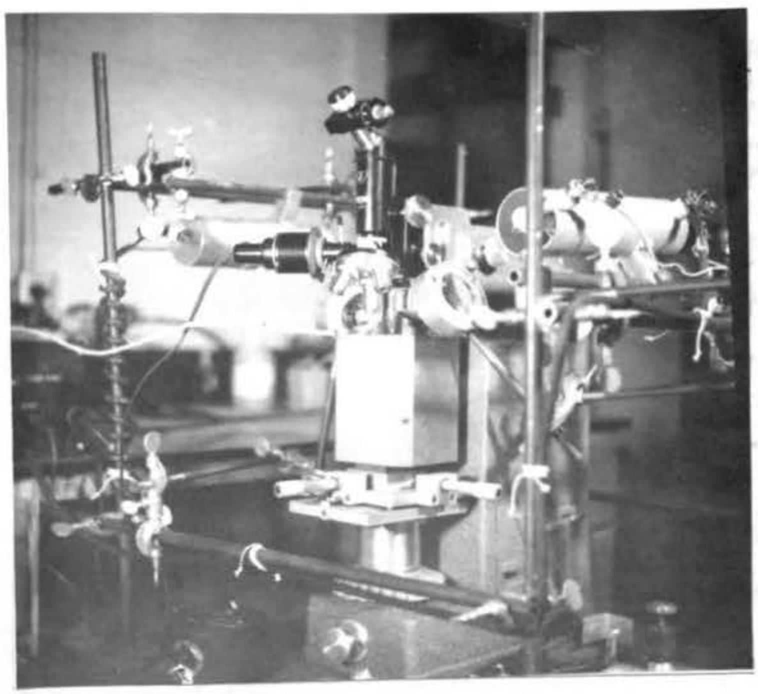
Samples were secured to the sample stage mounted atop an adjustable column or to a special sample holder that was then placed on the sample stage. The sample stage was provided with longitudinal and transverse micrometer adjustments for positioning the sample beneath the indenter.

The indentations were measured using an attached Bausch and Lomb microscope. This was provided with internal lighting and a filar eyepiece.

The sample holder is shown in position in Figure I and by



Experimental Apparatus



Experimental Apparatus

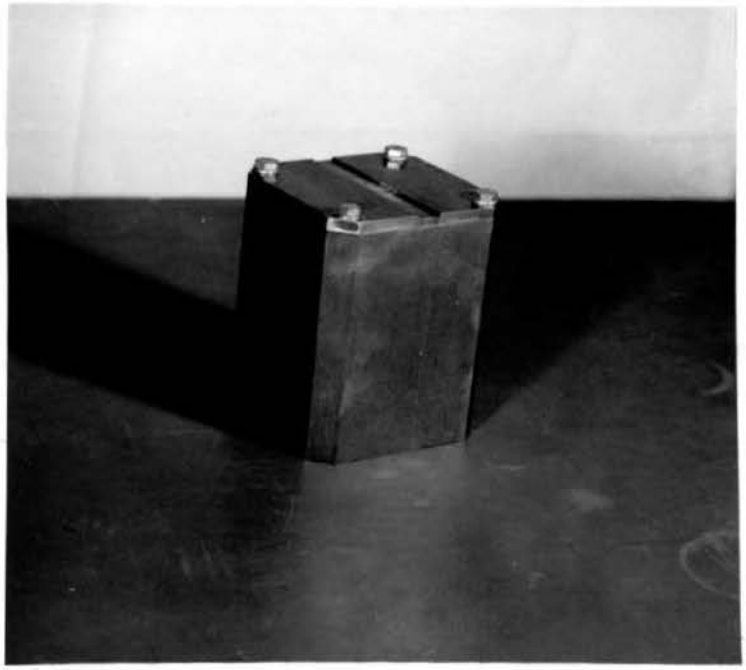
Figure I

Experimental Apparatus

itself in Figure II. This sample holder was produced for the author by the Mechanical Engineering Department of the University of Missouri at Rolla. The body of the sample holder was machined from a block of steel. The cylindrical recess in the center is for coolants. The copper top was provided with copper fins to insure good thermal contact with the coolant. The slot in the top, above the fins, was for the sample specimen. The top and bottom of the sample holder were surface ground parallel to make sure that the indenter made contact with the sample at the same height. Correct allignment was insured by the inclusion of a locating pin and four bolts.

Sample illumination was provided by two 500 watt General Electric T3 infrared lamps. The lamp holders and reflectors were also fabricated by the Mechanical Engineering Department. A lamp and holder-reflector unit is shown in Figure III. Since overheating would quickly destroy the lamps, centrifugal blowers were provided. A one inch diameter hole was provided in the holder-reflector to be used as the source of radiation. Holes of one quarter, one half, and three quarters of an inch were also provided in a ring that may be superposed over the original opening.

The lamps were controlled via a microswitch, operated by the actuating lever of the microhardness tester, and a solenoid operated switch. The microswitch setup is shown in Figure IV and the solenoid switch and control box in Figure V. A complete electrical schematic is given in Figure VI. When the actuating lever of the microhardness tester operated the microswitch, the solenoid switch was closed and the infrared lamps came on. The microswitch was adjusted to close seven seconds before the indenter contacted the

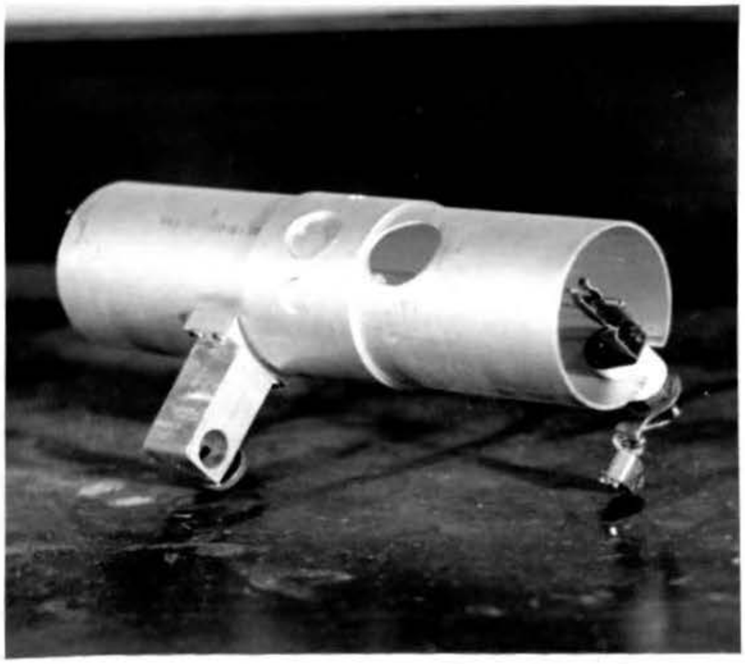


Sample Holder - Assembled

Sample Holder - Disassembled

Figure II

Sample Holder



Infrared Lamp Assembly

Infrared Lamp and Holder - Reflector Disassembled

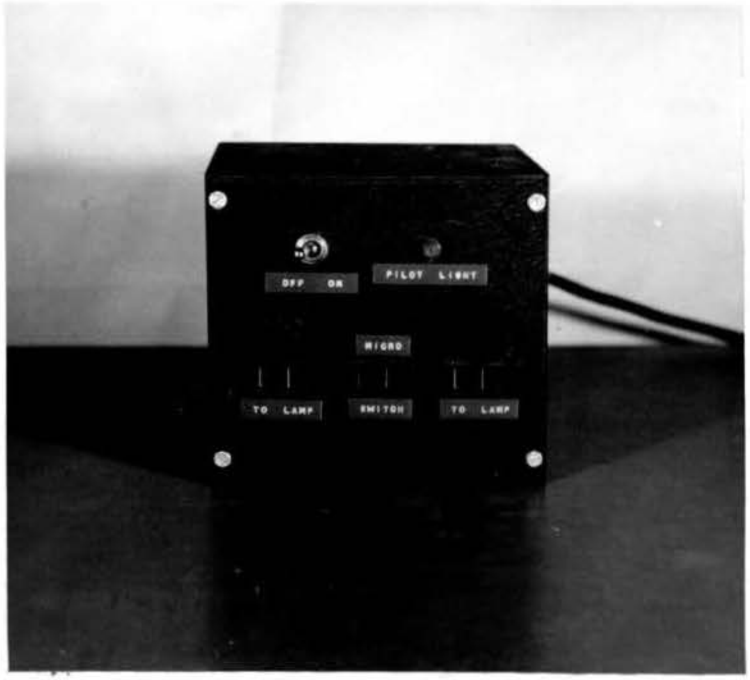
Figure III

Lamp Assembly

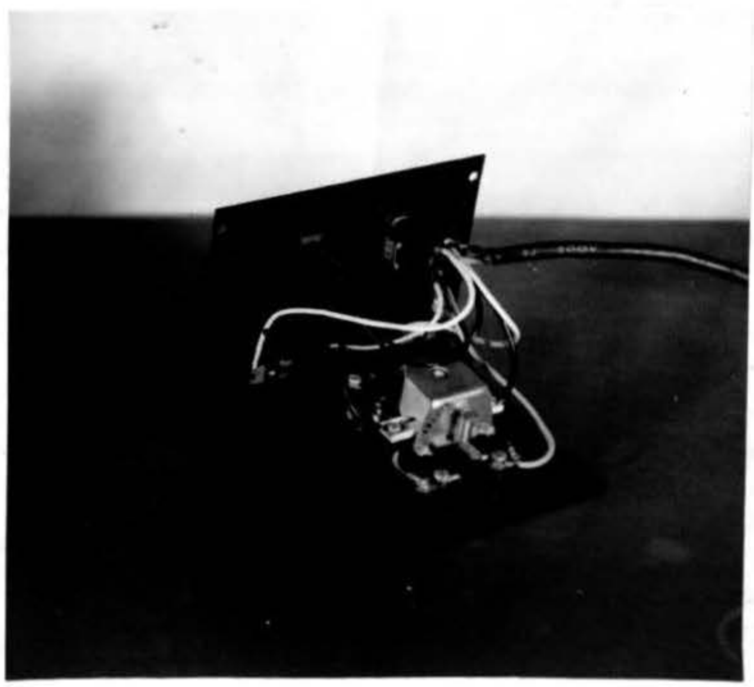
Microswitch Installation

Figure IV

Microswitch Installation



Lamp Control Box - Exterior



Lamp Control Box - Interior

Figure V

Lamp Control Box

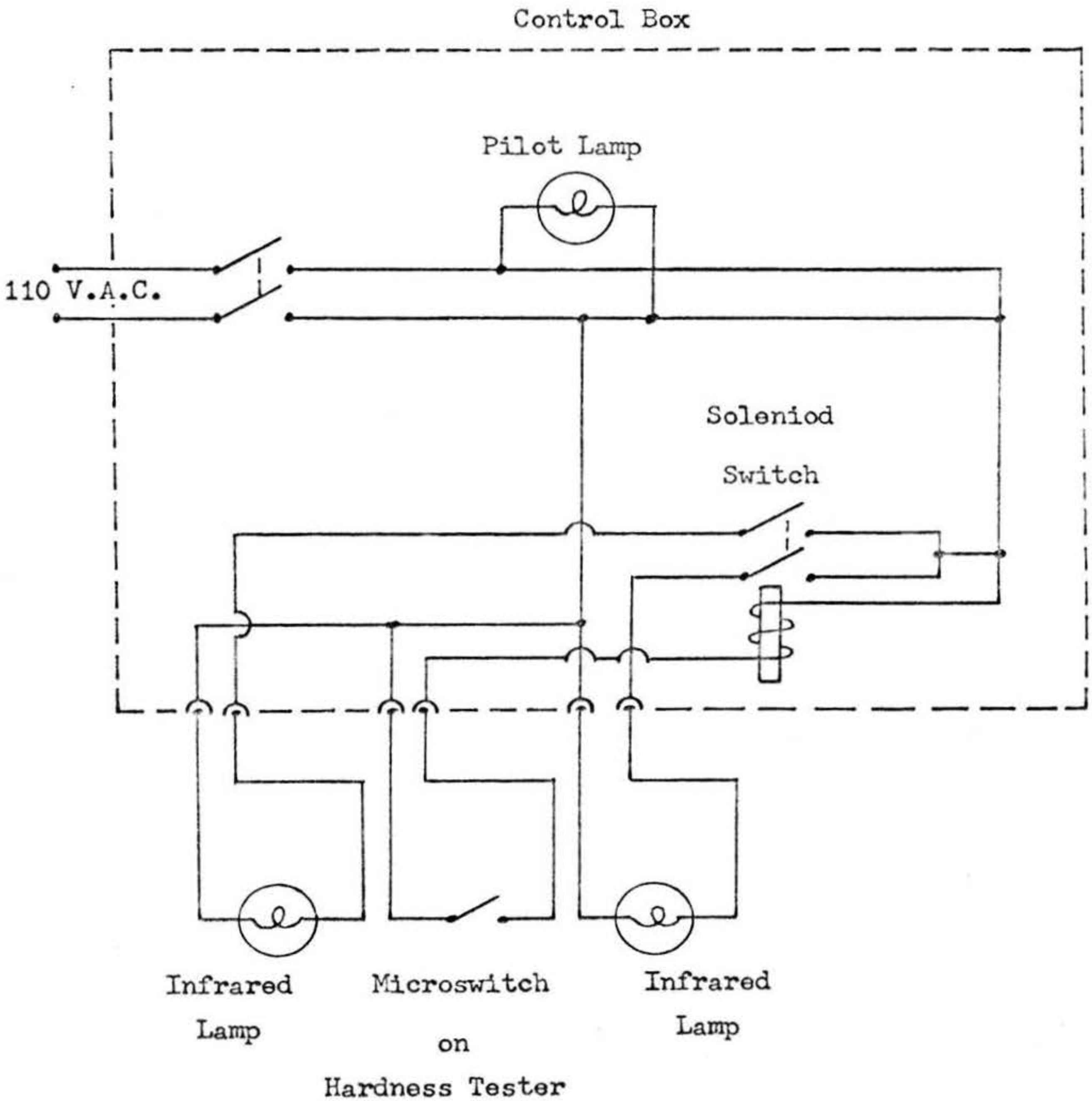


Figure VI

Electrical Schematic

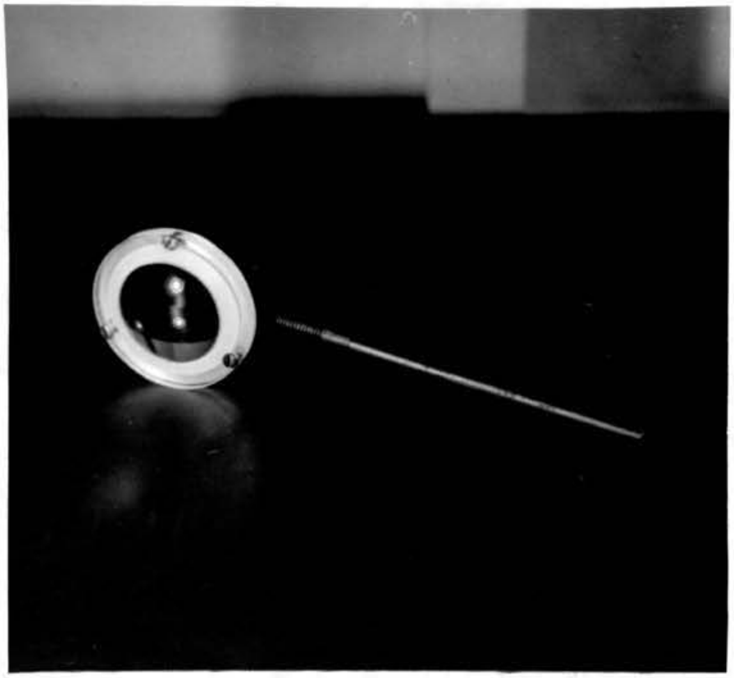
sample surface.

Fused quartz lenses were used to condense the radiation emanating from the infrared lamps and focused the radiation on the area in which the indentation was being made. The lenses were purchased from the Amersil Quartz Division of Engelhard Industries, Incorporated. A focal length of four and one half centimeters was necessary to produce maximum illumination. A lens and holder-reflector unit is shown in Figure VII. Two sets of lenses were necessary to insure that there were no shadows formed on the surface of the sample.

Room temperature measurements were made using a mercury thermometer directly readable to one hundredth of a degree centigrade.

For measuring sample temperatures, a Chromel-Alumel thermocouple was used. Millivolt readings were taken with a Leeds and Northrup potentiometer. The potentiometer was adjusted to the room temperature reading before making sample readings. As absolute temperature readings were not stressed in this research, only relative temperatures were necessary. Therefore the thermocouple was not calibrated. Millivolt readings were converted to temperatures using a Handbook of Chemistry and Physics.

A Knoop diamond indenter was used in this surface study. Due to the $172^{\circ}\ 30'$ included angle of the longitudinal angle, the indentation was much longer than it was deep. The particular Knoop indenter used had an indentation diagonal to depth ratio of 11.64 to 1.00. This high ratio allowed small depths of penetration for studying this surface phenomenon and still provided a diagonal that could easily and accurately be measured.



Lens and Lens Holder - Assembled

Lens and Lens Holder - Disassembled

Figure VII

Lens Assembly

All of the lighting equipment was fastened to a framework comprised of quarter inch black iron pipe. Flexibility was provided by the use of clamps throughout as fasteners. The framework was independent of the table carrying the microhardness tester as the vibration from the lamp cooling blowers affect the indentations.

The experiments were performed on single crystal samples of silicon. These samples were in the shape of bars measuring 0.6 x 0.25 x 0.08 inches. Only extrinsic silicon were used. Both N and P type silicon were used. Estimated impurity concentrations ranged from 10^{14} to 10^{19} impurity atoms per cubic centimeter*.

*See Appendix B for the calculation of impurity concentrations.

B. Preliminary Experiments

It was necessary to make several adjustments and perform preliminary experiments before proceeding with the experimental work actually dealing with the photomechanical effect.

It was necessary to adjust the height of the column supporting the sample holder so that the indenter would make contact perpendicular to the surface of the sample. This was necessary to write the equation for determining the Knoop Number accurately*. (Since it is the wall area of the indentation that determines the hardness, but it is the diagonal of the indentation that is measured, the proper relation between the two must be maintained.) Also, it was necessary to adjust the counterweights on the arm holding the indenter so that the weights in the weight pan would provide the only load for the indenter.

The Bausch and Lomb Filar Eyepiece was calibrated by measuring a known gage length from a Bausch and Lomb standard. Conversion factors, for converting filar units to microns, were found for the ten, fifty, and ninety power microscope objective lenses. For the conversion factors to be accurate, the crosshair of the filar eyepiece must be perpendicular to the length to be measured, must use the RIGHT HAND edge of the crosshair as the measuring edge, and the point to be marked by the crosshair must be approached from the LEFT only.

Since the Knoop Diamond Indenter used in these experiments did not conform perfectly with the definition of a Knoop Indenter,

* See Appendix A for a discussion of Knoop Hardness Numbers.

it was necessary to calibrate the indenter against a known sample. A standard reference block was included as equipment with the micro-hardness tester. Numerous indentations were made in this block in order that a correction factor might be obtained to be applied to later evaluations.

One preliminary experiment was run to determine the feasibility of running future experiments at low temperatures. To produce the low temperatures sought, the coolant recess in the sample holder was filled with dry ice and acetone. The surface of the silicon sample was kept clear of frost formation by keeping the surface covered with a thin layer of acetone. The temperature of the sample was read by fastening a Chromel-Alumel thermocouple under one of the bolts holding the top to the body of the sample holder. Due to the slow temperature change with time, it was felt that this adequately represented the temperature of the sample. Also, due to the qualitative nature of the experiment, more accurate measurements were not necessary.

One preliminary experiment on the photomechanical effect was made to demonstrate its existence and to determine the focal length of the quartz lenses to be used. As in all experiments, the silicon sample was secured to the sample holder by silver printed circuit paint. The silver paint provided a secure mounting method and excellent thermal conductivity. An indenter load of ten grams was used. Lenses for focusing the infrared radiation had focal lengths of approximately fifteen centimeters. As in all of the experiments, the indentations were made in two parallel rows, one row being the indentations made in the absence of the radiation and the other being made with illumination. The long diagonals of the indentations were parallel to the rows of indentations. By taking measurements in this manner, it can be assumed that the average values taken from the respective sets of indentations would be representative of the silicon sample.

A final preliminary experiment was performed to determine the effect of temperature on the indentation hardness of silicon. The body of the sample holder was heated by filling the coolant recess with water and boiling the water with an electric heater. After the sample holder body had come to equilibrium, the top, with the sample attached, was bolted on and the assembly was put in position on the microhardness tester. A Chromel-Alumel thermocouple was bolted to one corner in order to read the temperature. The cooling rate was slow enough that the thermocouple gave an accurate enough indication of the sample temperature.

C. Photomechanical Experiments

In order to show that the photomechanical effect exists, it was necessary not only to demonstrate the effect, but also to discount the possibility that it is caused by an experimental method or a particular sample.

With this problem in mind and the desire to tabulate other characteristics, seven experiments were carried out. These experiments were the determination of the effects of surface preparation, changes in surface properties after surface preparation, temperature, temperature increase due to infrared illumination, impurity concentrations, indenter load or penetration, and the crystallographic orientation.

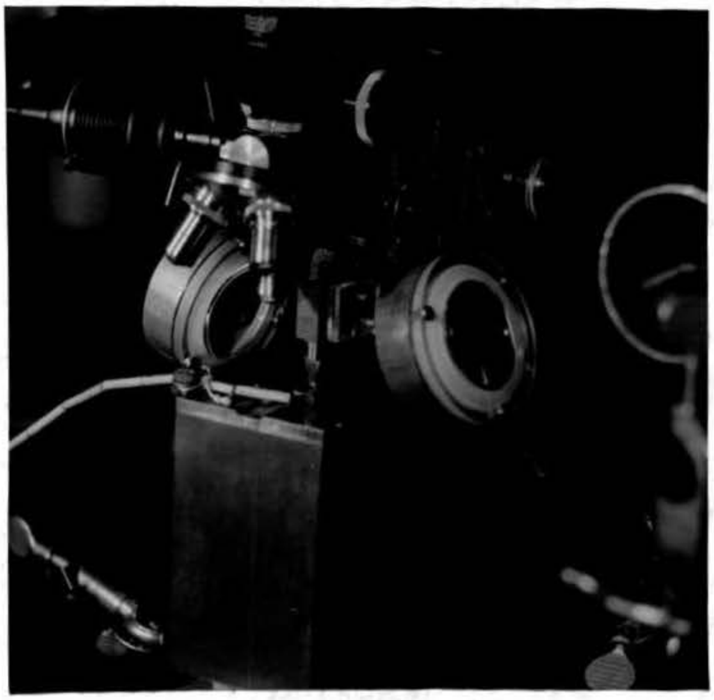
Surface preparation was studied first so that information gathered here could be used to improve later work. Three surface preparations were studied. Determinations were carried out on identical specimens or the same specimens. The first determination involved observing the degree of softening caused by radiation of a surface that had been etched over a year prior to the experiment. This sample was exposed to the atmosphere at all times during this aging period. In the second experiment, the surface of the same sample was etched with a solution of three parts by volume concentrated HNO_3 and one part concentrated HCl. The samples were etched in hot etchant. The third study involved CP-4 as etchant. CP-4 is comprised of nine parts by volume of concentrated HNO_3, seven parts glacial acetic acid, and four parts concentrated HF. Fresh etchant was prepared each time a sample was etched as its properties deteriorate within a few hours. Etching proceeded so rapidly that only about a half of a minute was necessary to prepare the surface. Longer exposures produced pitting and discoloration. Each determination entailed making parallel series of indentations both with and without infrared illumination. Approximately fifty indentations were made during each condition of etch and illumination so accurate average hardnesses could be found.

In conjunction with the preceeding experiment, a run was made on the CP-4 etched sample one day after the first run to see if there was any change in hardness. The indentations for this determination were made parallel to and beside the indentations from the previous day so the results could be attributed totally to relaxation.

Initially temperature-hardness characteristics were found by cementing the silicon sample to the sample holder with silver paint and heating the sample and sample holder to 200°C in a heat treating furnace. By the time the sample holder could be brought upstairs, have the thermocouple attached, and be mounted the temperature dropped to 100°C. Far more important, it became obvious that the surface of the sample was being slightly oxidized, thereby ruining the results since the properties of the oxide and not the silicon were being measured. It was feared that the thermal shock of applying the silver paint and the sample to the sample holder after the sample holder was heated would break the silicon crystal. Therefore, another method was used to raise the temperature of the sample holder. The sample was attached to the cover of the sample holder with silver paint and set aside. The coolant recess in the body of the sample holder was filled with water. This water was then heated to boiling using an electrical heating element. The top could then be attached without imparting as great a thermal shock as would otherwise have been necessary. This method produced almost as high a useful starting temperature as the furnace heated method. In this case, small series, approximately ten, of indentations were made and the average temperature found using a Chromel-Alumel thermocouple bolted to the top of the sample holder. It was felt that due to the exceptional thermal conductivity of the copper, the temperature recorded by the thermocouple would be very close to that of the silicon sample. Series of indentations made in the dark and under illumination were made alternately and with the indentations side by side and parallel. Series were made every ten degrees centigrade, from 80°C down to room temperature. Room temperature hardness measurements taken at the end of a run were compared with similar measurements taken before heating to make sure the sample surface had not oxidized.

In order to demonstrate that the softening of the surface was not due to heating, another experiment was made to determine the temperature increase due to illumination. For this experiment the thermocouple was placed beside the silicon sample and painted several times with silver paint to insure good thermal contact with the sample. The radiation from the lamps was focused on the silicon sample just beside the point where the thermocouple was affixed. Figure VIII shows the experimental setup. The lamps were turned on and the change in temperature of the sample was found.

In order to show that the photomechanical effect is not an anomaly due to a particular sample and to obtain data on the effects



Experimental Setup for Finding the Temperature Rise Due to Illumination

Figure VIII

Experimental Setup - Temperature Rise

of impurity, eleven runs were made on N and P type crystals of varying impurity concentration. There were six N type and five P type samples. All were freshly etched with CP-4. The experiment consisted of finding the photomechanical effect for each impurity concentration. As previously, this was done by making parallel rows of indentations both with and without illumination. Absolute values were used to determine the effects of the impurity concentrations on the lattice.

It has been reported that the electromechanical and the photomechanical effects are surface effects. To test the validity of this statement, a further set of runs was made using different indenter loads. This, in effect, varied the depth of penetration. Besides determining whether or not this is a surface effect, a side benefit was derived in that the optimum indenter load for use with the other experiments could be found. All experiments were performed on the same sample. Parallel rows of indentations were made, two rows for each different indenter load. One row was, of course, made in the dark, the other under illumination. Indenter loads were one, two, three, four, five, six, eight, ten, and thirteen grams.

As a qualitative experiment in the determination of any crystallographic effects, an experiment was performed in which the angle of the rows of indentations, relative to the long side of the sample, was varied. In all other experiments, the rows were parallel to the long side. Four sets of two rows each were made. These were at angles of zero, thirty, sixty, and ninety degrees to the long side. As time did not permit the vast number of runs necessary to determine which crystallographic directions were most important, the experiment only answers the question of whether or not there is a crystallographic anisotropy.

In an effort to ascertain whether it is only infrared radiation that is responsible for the photomechanical effect, an experiment was performed in which a fleshly prepared sample was indented in darkness, under illumination, and under illumination, but with a thin sheet of glass between the source and the sample. The glass served as a filter to eliminate most infrared wavelengths. Fifteen careful indentations were made under each set of conditions. Extra care was taken to eliminate vibration. (Mainly by making indentations when the building was empty.)

All experiments were performed under as identical of conditions as possible.

IV. DISCUSSION OF RESULTS

A. Preliminary Experiments

The results of the calibration of the Bausch and Lomb filar eyepiece are given in Table I in the appendix. It should be noted that these average conversion factors are only good when the eyepiece is used on the microscope mounted on the Kentron Micro Hardness Tester.

The average of fifteen indentations in a standard reference block was found to have a value 1.6 percent higher than the stated gage value. Subsequent hardness values were adjusted to compensate for this fault. The actual hardness values for this experiment are listed in Table II.

The investigation into the use of low temperatures revealed that it is possible to obtain and perform experiments at dry ice temperatures, although it is not too practical. Due to the low temperature of the sample holder and the high humidity of the room, the frost build-up was somewhat of a problem. The frost could be kept off the surface of the sample by applying a film of acetone to the surface. It was found that by clamping the top on tightly with the four bolts, temperatures near -140°C could be maintained for approximately thirty-five minutes. This means that the dry ice must be replenished once in the middle of most of the important runs. Dry ice consumption should not run more than one pound per hour plus three pounds to initially cool the sample holder down. Due to the time involved in obtaining and maintaining the dry ice temperature, it was felt that it was not practical to use that procedure in an investigation requiring so many determinations.

It has been reported (7) that low temperatures greatly enhance the electromechanical effect. It is expected that a similar result would be found for the photomechanical effect.

The results shown in Table III indicate a rather small photomechanical effect. However, it did establish that there is such an observable softening. The low figure of 8.9 percent is undoubtedly due to the low level of illumination. In this experiment, lenses of rather long focal length were used. The higher values found later were due to the new short focal length lenses purchased.

The temperature-hardness relationship turned out as anticipated. Table IV and Figure IX show the minor decrease in hardness as the temperature is raised. One standard deviation is shown to each side of the sample points reproduced on all graphs. This is done to illustrate the large spread to be expected when making microhardness measurements. The 82.5°C upper temperature limit shown in Figure IX was quite adequate for the investigation.

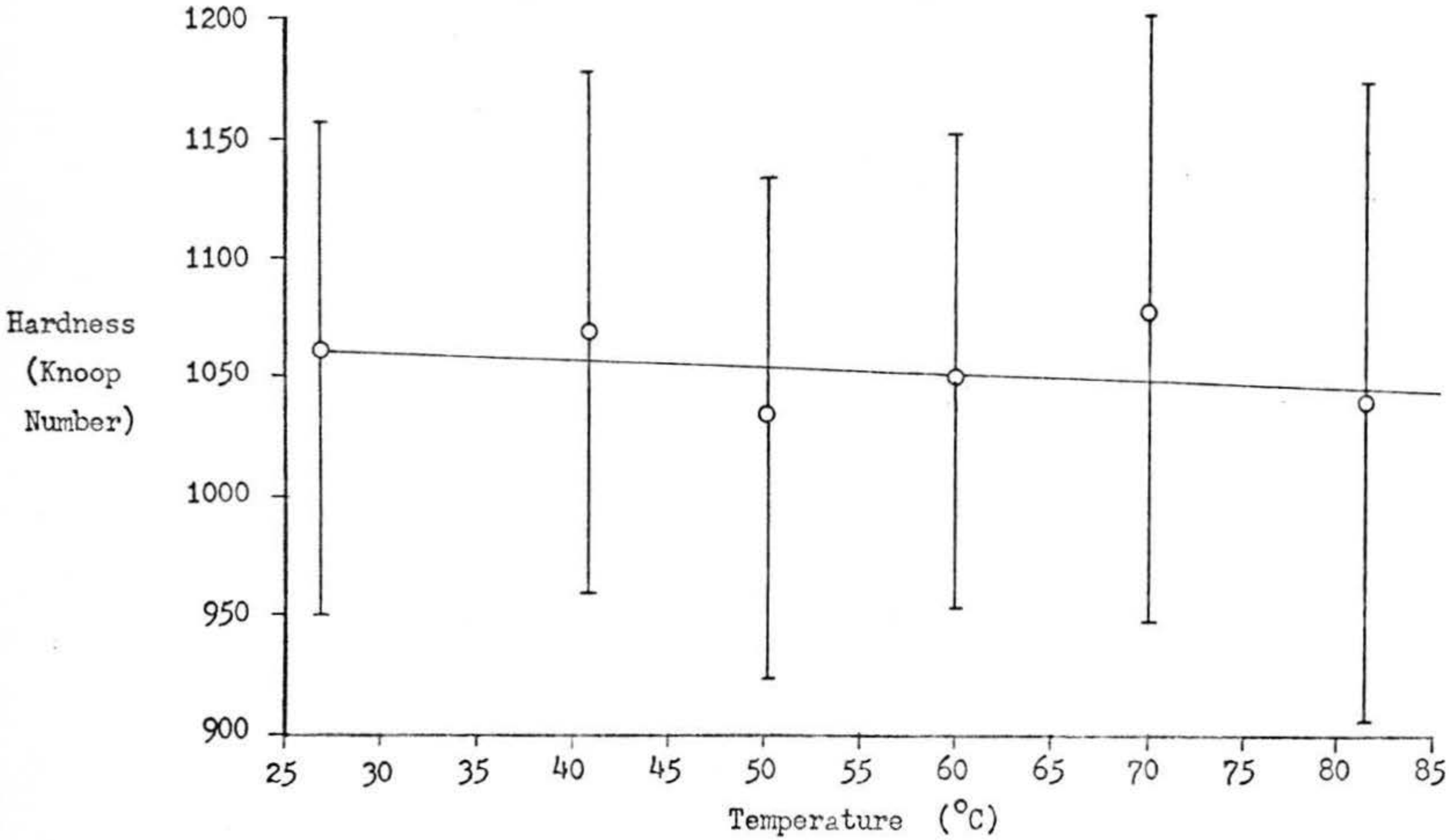


Figure IX

Effect of Temperature on Hardness

B. Photomechanical Experiments

Surface preparation experiments indicated that there was a deterioration of the surface properties of silicon with long exposure to the atmosphere. A sample that had been aged in excess of one year had a high hardness and a small photomechanical effect. This anomaly was probably due to surface oxidation. Since the indentations are shallow, the properties of the oxide layer were largely determined rather than the properties of the silicon. Complete data is listed in Tables V A and V B in the appendix. Prolonged etching in the 3 HNO_3 / 1 HCl solution produced no noticeable effect on the oxide layer. The results obtained were almost identical to those obtained for the aged surface. Further information is given in Tables V C and V D. However, etching in the CP-4 solution did produce a large effect on the properties of the surface. It was found that the dark hardness decreased by 18 percent from the unetched to the CP-4 etched surface. Simultaneously the photomechanical effect increased by 56 percent. Etching action was so vigorous that thirty seconds was ample to clean the surface. Longer durations produced severe pitting and discoloration of the sample. Etching action was evidenced by bubbles being formed on the surface of the sample. The CP-4 etched surface had a much lower hardness and a higher photomechanical effect. Since the etching was not allowed to proceed to the point of ruining the surface, it is felt that the results actually reflect the true values for silicon. Detailed information is given in Tables V E and V F.

There was a possibility, however, that there might have been some surface strain left immediately after etching. The experiment to check for relaxation did find an additional softening of the surface after one day aging. The dark hardness decreased by 14 percent, but the photomechanical effect, percent softening, remained unchanged. Contrary to (7), it was found that this additional softening was not due to oxidation since the aged samples, assumed to be oxidized, had high hardness numbers. It is thought that this change is the result of relaxation of surface strains. In subsequent experiments the samples were etched in fresh CP-4 and were aged a uniform amount before use in order that a constant relaxation would have occurred. The results of the relaxation experiment are given in Table V G.

The temperature-hardness characteristics shown in Figure X parallels the results obtained in a similar determination on the electromechanical effect in (7). It is especially interesting to note the enhanced electromechanical effect produced at low temperatures. It is obvious that the two lines are approaching one another as the temperature is raised. It is well known that increasing the temperature increases the concentration of conduction electrons and that photons of proper energy will also produce conduction electrons. In this experiment these mechanisms are in competition to see which will excite the constant number of electrons available. From this competition the shape of the curves in Figure X can be explained. It is the author's contention that the decrease in photomechanical effect with increasing temperature is due to the increasing probability that an electron will find a sufficiently energetic thermal phonon before being acted upon by an optical photon. At low temperatures, there are very few phonons with sufficient energy to excite an electron, therefore, almost all excitation

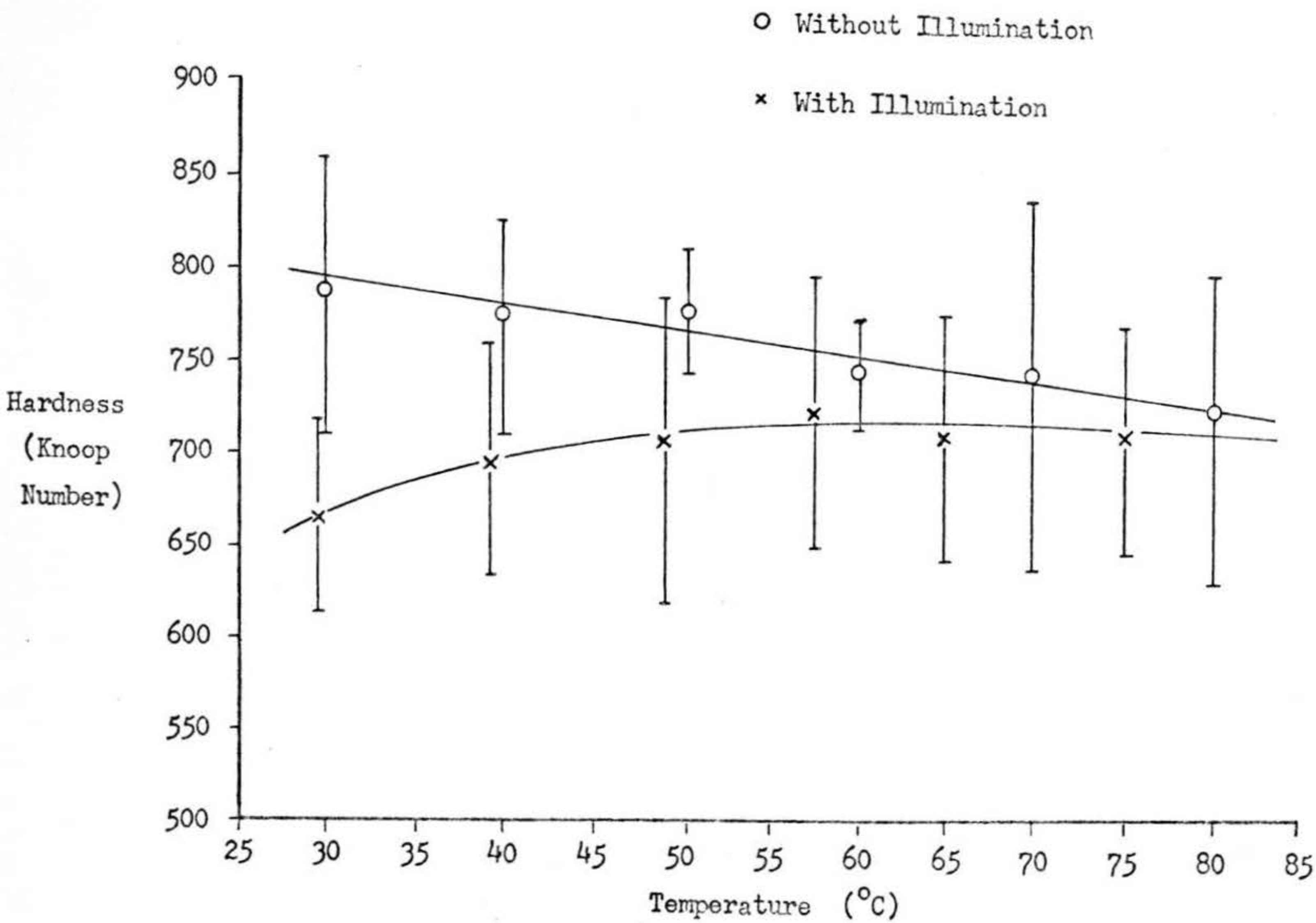


Figure X

Effect of Temperature on Hardness and the Photomechanical Effect must come from photon-electron interactions and a high photomechanical effect is observed. However, due to the low level of illumination, the thermal phonons are numerically more prevalent than the photons at the higher temperatures and therefore photon-electron interactions are proportionally fewer and there is a small photomechanical effect observed. A similar mechanism would explain the analogous results obtained in (7). In that determination a constant current density was used. This would also form a source of energetic particles of constant number. This would correspond to the constant level of illumination used in the present investigation.

It would seem reasonable that greater photomechanical effects might be produced at subambient temperatures. This has been noted in the case of the electromechanical effect (7). Since a series of readings could not be made at the same temperature, the temperatures indicated in Table VI are average temperatures. There was a 2°C spread at the higher temperatures. This spread decreased to a negligible amount as room temperature was approached.

It is very important that it be shown that the softening of the silicon crystals was not due to heating. In other investigations, (1) (5) (8), this fact was assumed, although rightly so since the temperatures necessary to produce the degree of softening would have boiled their coolants. In the present work, a thermocouple attached to the sample indicated an increase in temperature of only 1.2°C. As can be seen from Figure X, this would produce a negligible amount of softening. This equilibrium temperature was reached after only forty-five seconds. The large heat sink provided by the sample holder is attributed to be the reason for the low temperature increase. It is felt that this definitely excludes any possible argument that heating is the source of the photomechanical effect.

It is interesting to note the dissimilarities in the present investigation and the one reported in (7) concerning the effect of impurity concentration. In the case of the P type impurities, there was no systematic response that can be explained by a simple theory, as is shown in Figure XI. It would seem reasonable that increasing impurity concentration would increase the hardness number due to increasing lattice strain. However, there are two important facts to be remembered when analyzing the results obtained. First, even the highest impurity concentration is only a trace amount and may not in this case cause a measureable increase in hardness. Secondly, the history of the silicon samples is unknown. It may be that different impurity elements were used and would therefore produce varying lattice strains and hardnesses. The data from the N type material did not have the large spread and does fit the theory of strain hardening. Also, the effect on the degree of softening can be explained very nicely. The N type material does exhibit a systematic behavior. In the illuminated condition, the hardness decreases linearly with increasing impurity concentration. This can be explained by noting that there is a greater probability that a given photon will encounter an impurity atom since there are more atoms available. Of course, the more photon-electron interactions, the more photomechanical effect. The information shown on Figure XII is in much better agreement with the previous work and also agrees with the conclusion drawn above. Figure XIII shows the effect of

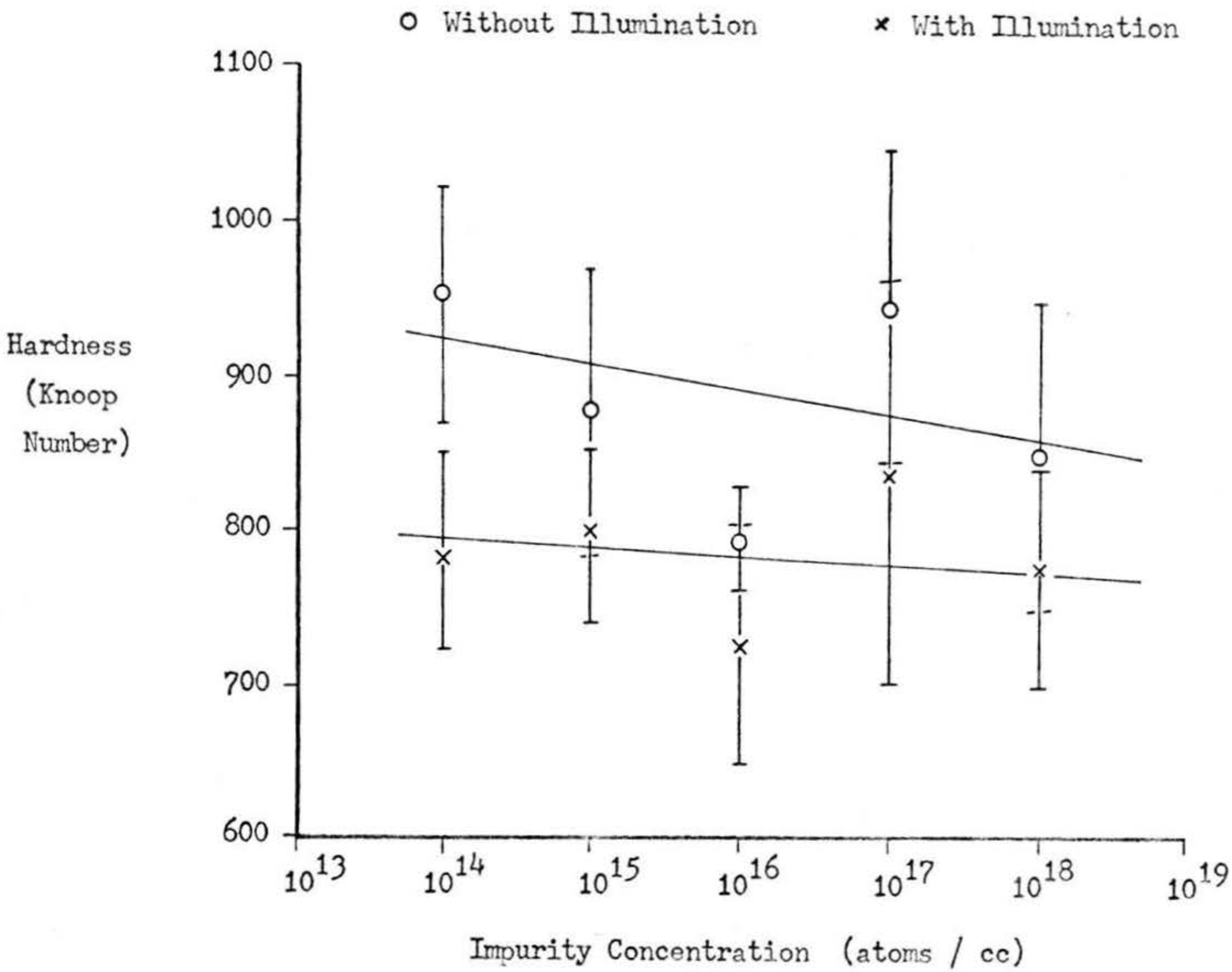


Figure XI

Effect of P Type Impurities on Hardness

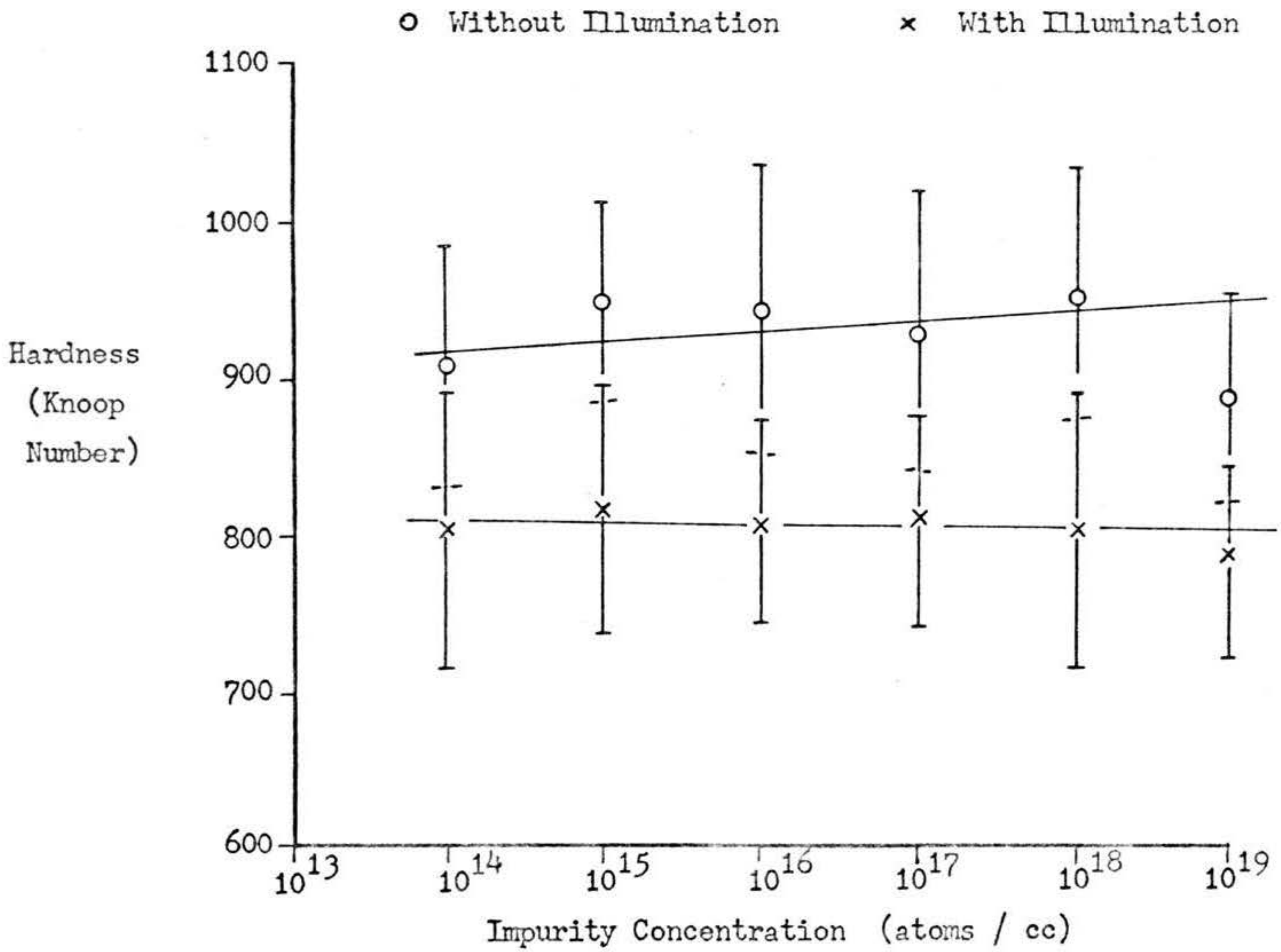


Figure XII

Effect of N Type Impurities on Hardness

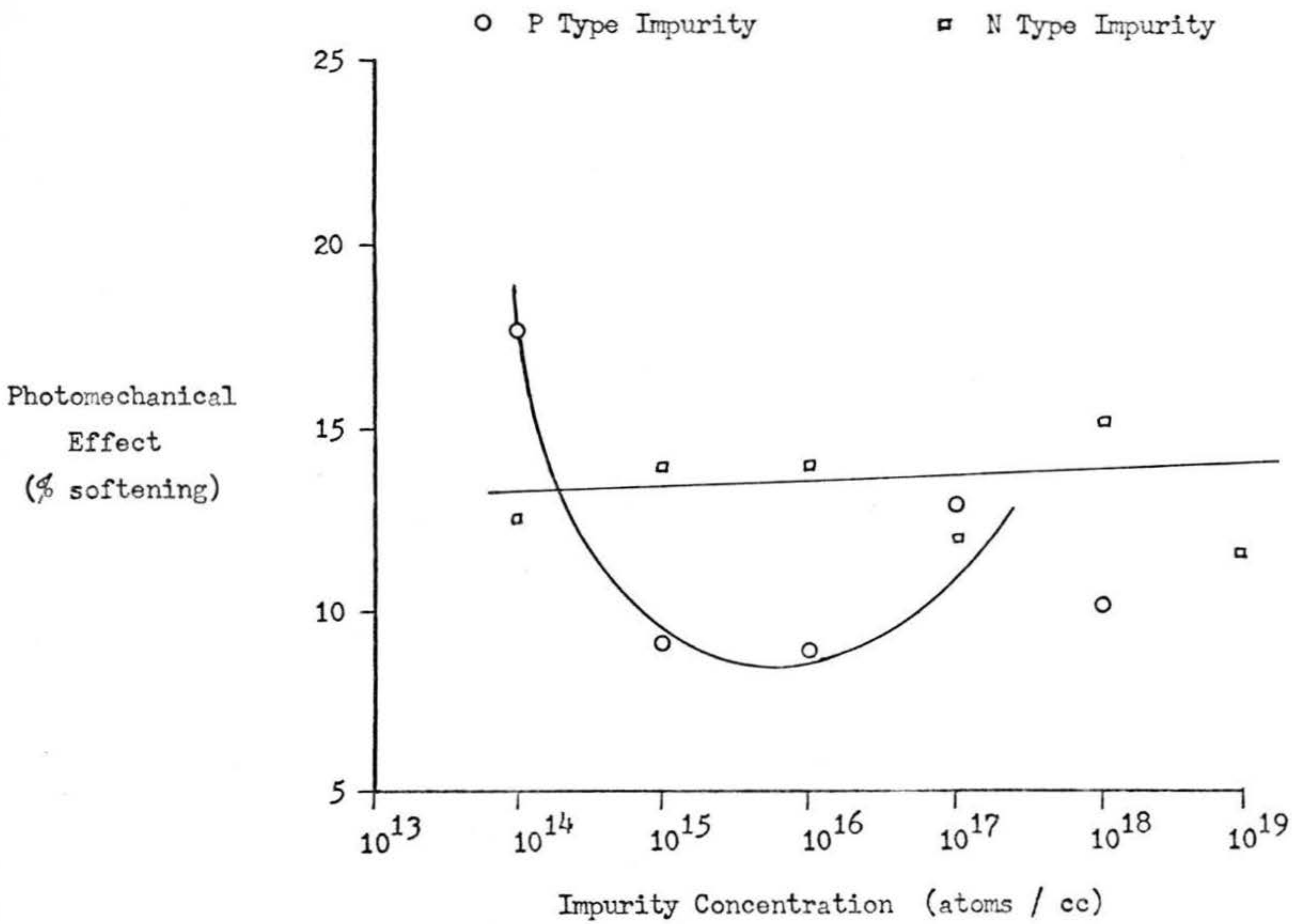


Figure XIII

Effect of Impurity Concentration on the Photomechanical Effect the impurity concentration on the photomechanical effect. The data for the P type material is not good and should be disregarded. While the fit is not good for the N type material, the fitted curve seems quite reasonable when examined in conjunction with Figure XII, and agrees with the theory. Complete data is available in Table VII.

The experiment in which the indenter load was varied in order to obtain varying depths of penetration, demonstrated that the effect is limited to the surface only. Figure XIV shows the sudden drop in the photomechanical effect as the indenter passed through the softened layer into the unsoftened bulk of the material. It is postulated that the low values obtained for the small loads were due to vibrations of the building. This would tend to lengthen the indentation and thereby decrease the hardness number. Figure XV is very similar to the ones found in (7). This again points up the similarity between the photomechanical and electromechanical effects. Figure XIV suggests that the surface layer is only 0.8 microns thick. This, coupled with the reports in (1), (5), and (7) that the layer is about two to three microns thick, tends to confirm the suspicion that the light source used in this investigation was not powerful enough. The number of excited electrons should vary linearly, to a first approximation, with the number of incoming photons. This is because it will take more electrons to absorb the increased number of photons. Since the concentration of available electrons is a fixed quantity, the volume and thereby the thickness will change with the level of illumination. The way to get more electrons is to go deeper into the sample. Therefore,

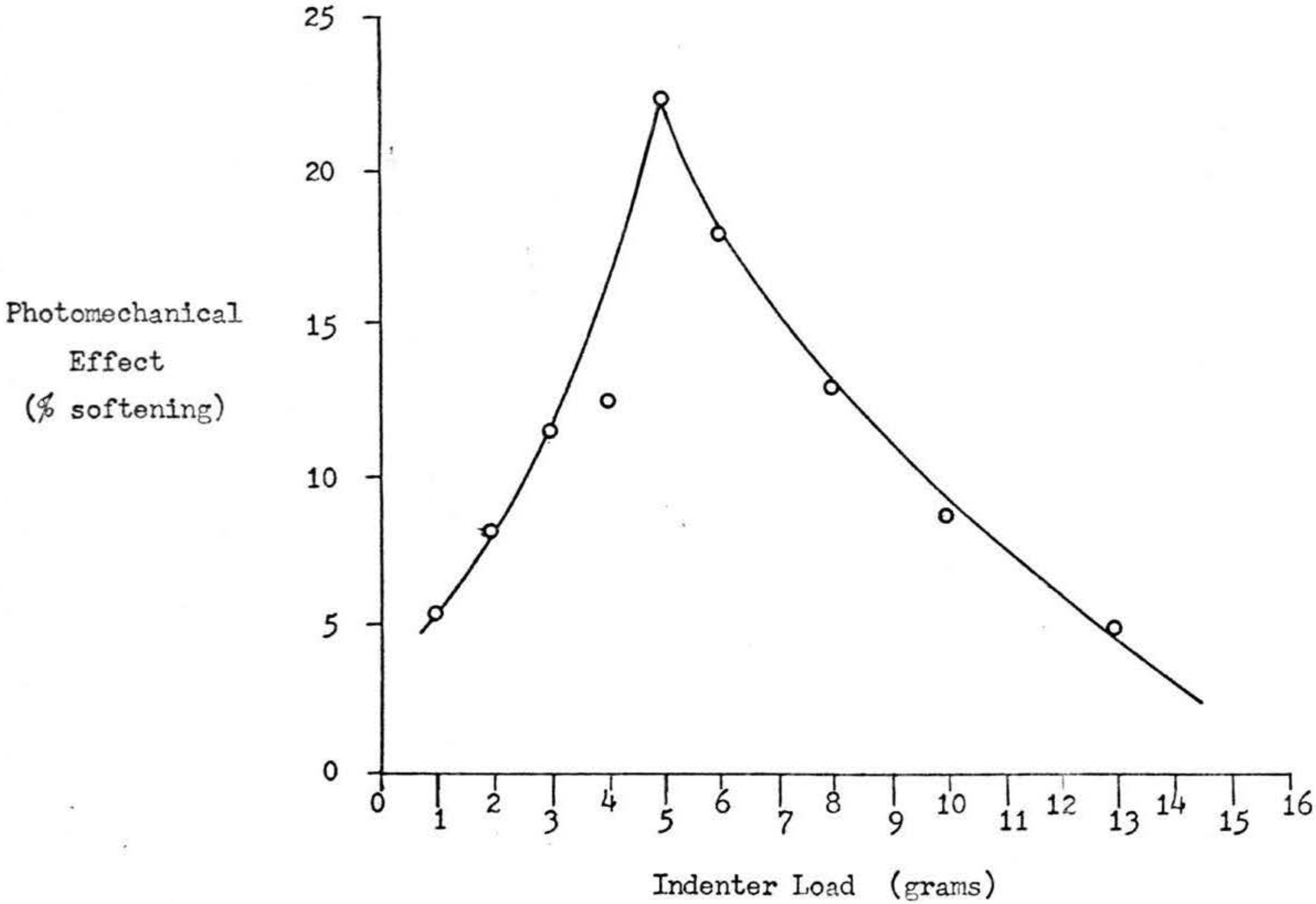


Figure XIV

Relation of Indenter Load to the Photomechanical Effect

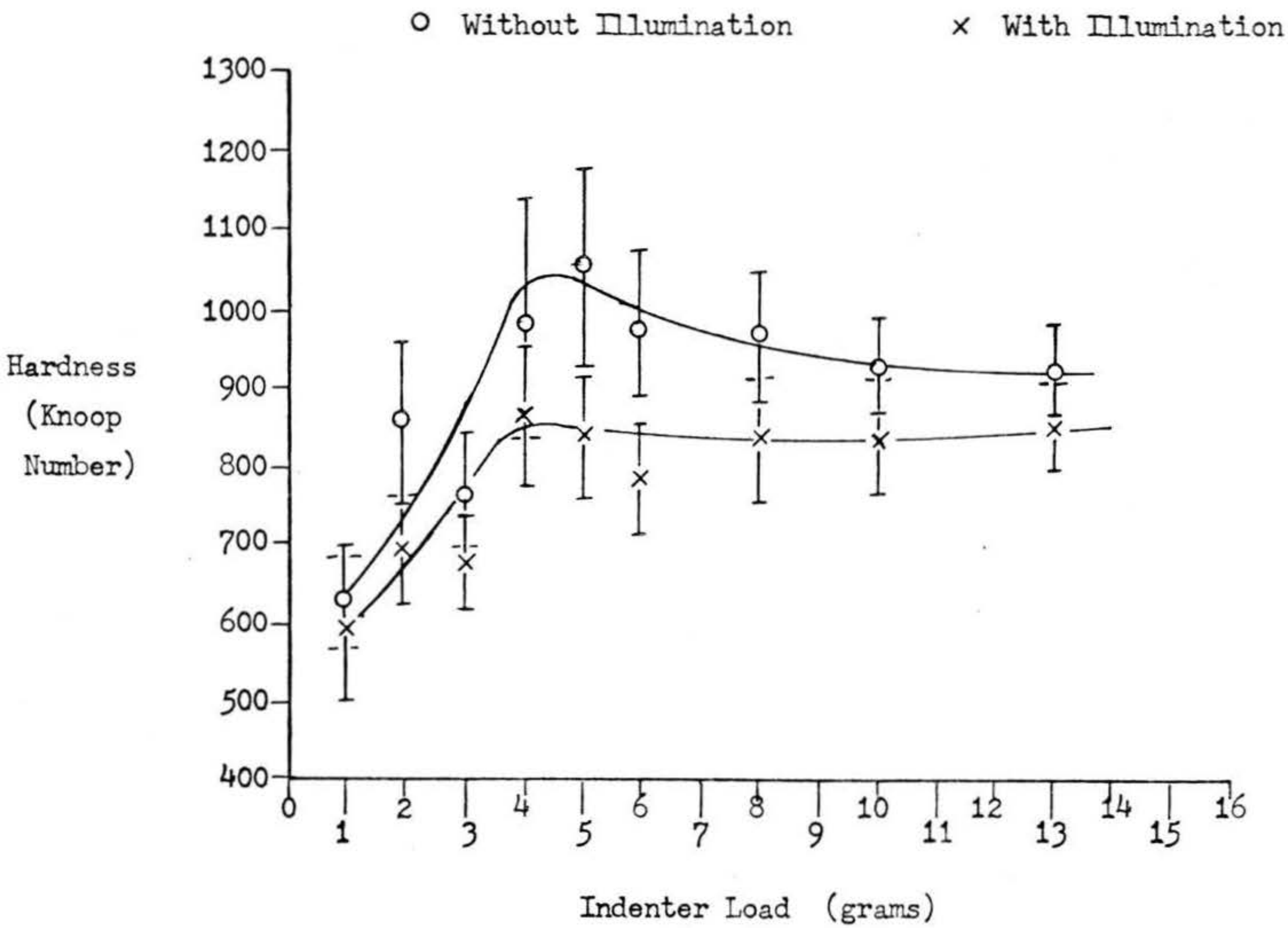


Figure XV

Relation of Indenter Load to Hardness

more powerful sources should make possible quite thick layers. The data from this experiment is contained in Table VIII.

However qualitative the experiment on crystallographic effects is, it upholds the findings reported in (10) and (11). There is obviously an anisotropy in the microhardness of silicon as shown in Figure XVI. There was observed a 13 percent change in the dark hardness as the sample was rotated. Probably just as important, there was also an anisotropy in the photomechanical effect. The change observed here was a very large 38 percent. It is obvious that crystallography can play a large part in the magnitude of the observed data. This relation is shown in Figure XVII. However, contrary to what was stated in (10), the anistropy was not destroyed by chemical polishing. The time did not permit a more complete determination, which would probably have given a more detailed insight into the anisotropy. It would be most interesting to see which planes were responsible for the maximum and minimum hardnesses observed. Additional information may be found in Table IX.

An original discovery made during this investigation found the limits on the possible wavelengths responsible for the photomechanical effect. Previously it was reported (1) that the wavelengths of interest must be between two and four microns. In the course of running the experiment in which the light source was filtered, the filter transmission characteristics were obtained using a Beckman infrared spectrophotometer. These results are shown in Figure XVIII. A comparison of the results of this experiment with those obtained during the determination of impurity effects checked very closely. Correlation of this fact together with the

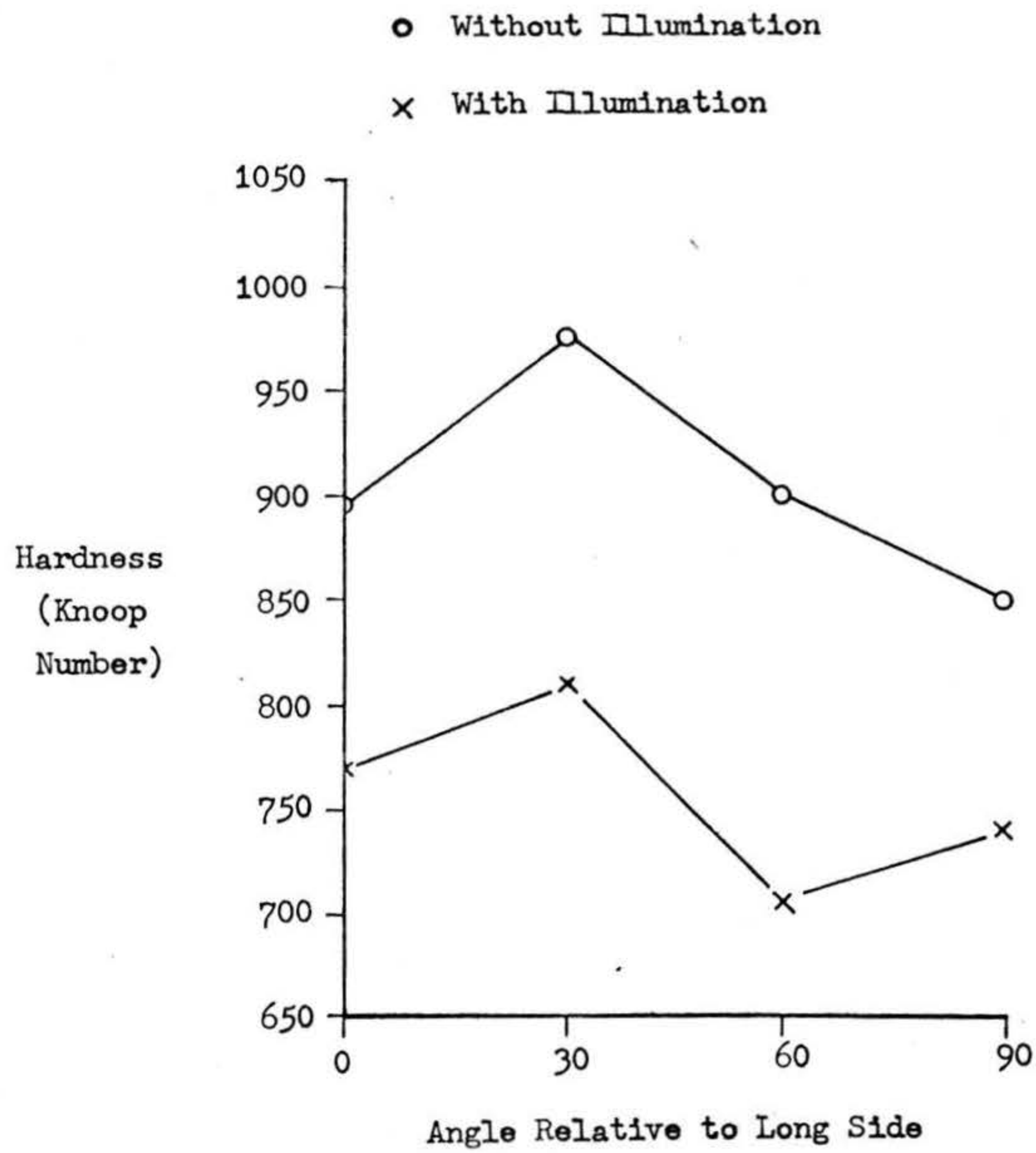


Figure XVI

Hardness Anisotropy

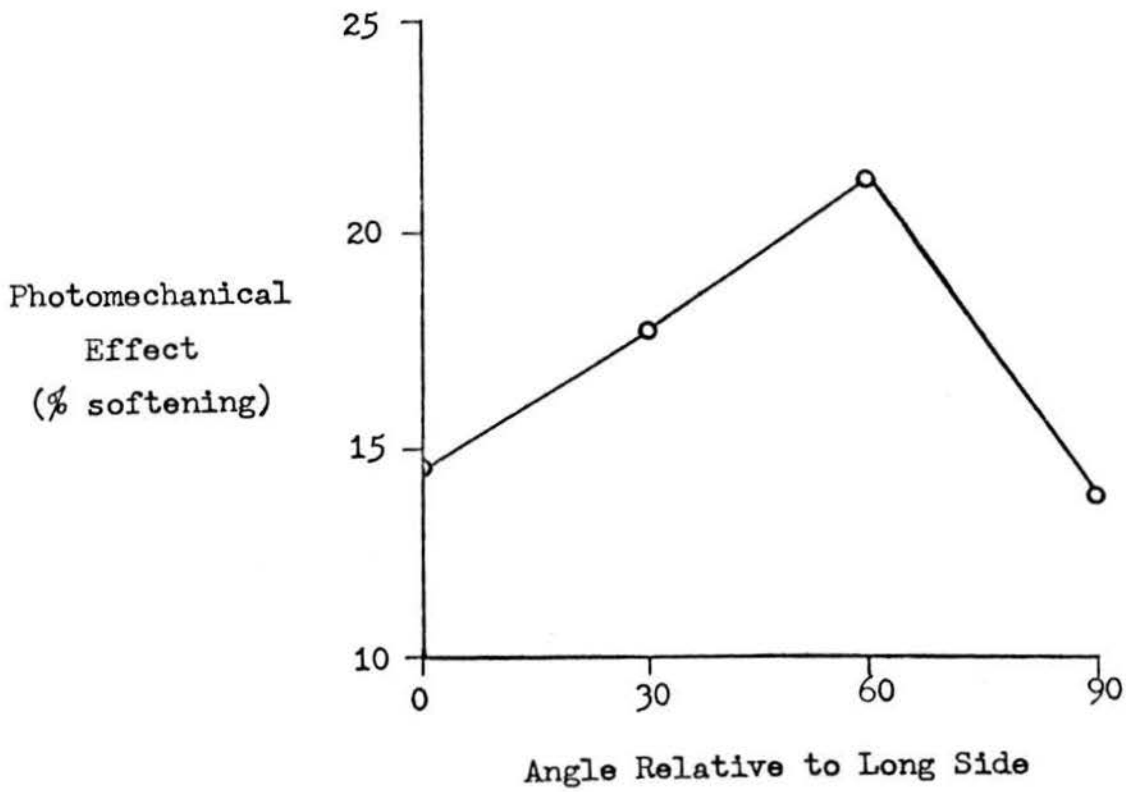


Figure XVII

Photomechanical Effect Anisotropy

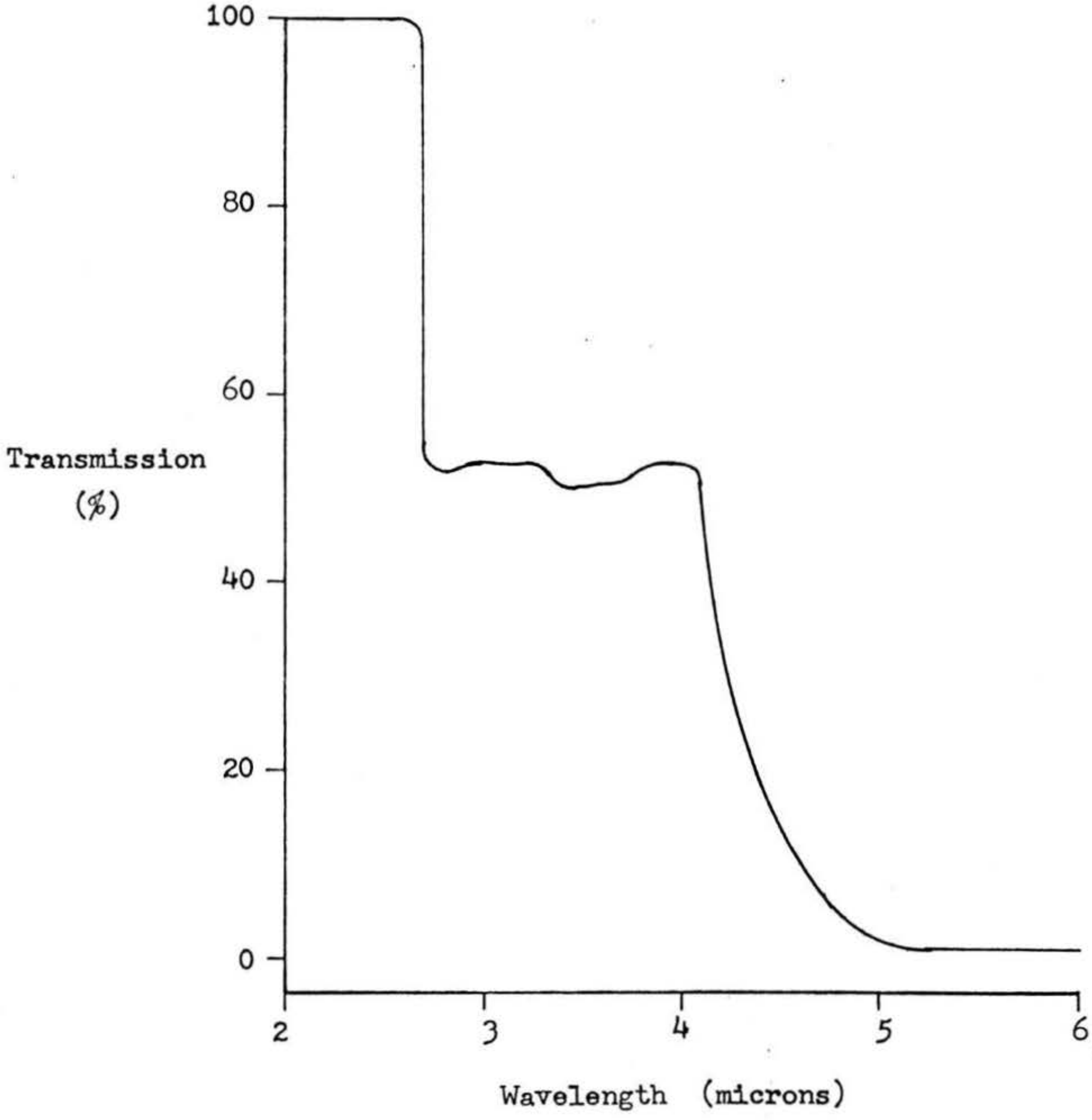


Figure XVIII

Transmission Characteristics of Glass Filter results of the transmission curve indicate that the wavelengths of interest must lie between 2.00 and 2.75 microns. It is of great interest to note that this wavelength corresponds to an energy of approximately 0.06 electron volts. This is very close to the value of the energy needed to excite electrons from donor levels or into acceptor levels. This suggests to the author that dislocations are the ultimate source of acceptor and donor energy levels. Therefore, physical properties indeed have an effect on the electronic energy configuration.

V. CONCLUSION

It is most important to note the similarity in the work described in (7) and the present investigation. It seems evident that the photomechanical and electromechanical effects have the same or very similar mechanisms.

It was found that a short etch in CP-4 was necessary to properly prepare the sample for investigation. Thirty seconds seemed to be a good etch duration.

The photomechanical effect washes out with increasing temperature. This is because electrons are excited to higher energy levels by phonons rather than by the photons since there are more of the former present that have the necessary energy at elevated temperatures.

It is important to note that there was only a very slight increase in the surface temperature of the sample upon illumination; certainly much too small to be the source of the softening.

There seems to be no definite relationship between the photomechanical effect and P type impurity concentration. Results were too erratic to show any characteristics. Results on N type samples indicate, however, that the photomechanical effect increases with increasing impurity concentration.

The effect is limited to a thin surface layer, in this case 0.8 microns thick. It is postulated that this thickness would increase with higher intensity of illumination and be more in line with the two micron figure quoted by others.

An anisotropy in the microhardness was observed and more important an anisotropy in the photomechanical effect. This would seem to be an important theoretical consideration in determining the detailed mechanism.

The narrowing of the band of possible effective wavelengths was probably the most important result of the investigation. It would seem quite a coincidence that the energy of this radiation has an energy very similar to that needed to excite electrons in extrinsic semiconductors. It would seem a very worthwhile project to make a determination of the applicable wavelength for use with intrinsic silicon.

A possible mechanism for the photomechanical effect is seen by the author. Simple Coulomb repulsion would account for a spread in partial dislocations if these dislocations had electrons trapped on their faces. If these electrons are excited away, there will not be this repulsion to impede movement. This explanation is meant only to illustrate a very basic mechanism. Detailed analysis would undoubtedly produce many other contributing factors.

It is recommended that further work be done at low temperature and a determination of the applicable wavelength for use with intrinsic silicon be made.

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VITA

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He has been enrolled in the Graduate School of the University of Missouri at Rolla since September, 1964. He is the recipient of a National Science Foundation Traineeship for the period September, 1964 to August, 1965.

APPENDIX

APPENDIX A

Knoop Hardness Numbers

Knoop hardness numbers are relations between an applied load and the resulting unrecovered projected area of the indentation produced. These numbers are only applicable to indentations made with the Knoop indenter. This particular indenter must be cut in the shape of a diamond-based pyramid. The longitudinal included angle must be $172^\circ\ 30'$ and the transverse angle $130^\circ\ 00'$. Because of the difference in diagonals of the impression, almost all of the elastic recovery takes place in the transverse direction.

The Knoop hardness number may be expressed by the formula:

$$KN = \frac{L}{A_p} - \frac{L}{Cp(l)^2}$$

Where

KN = Knoop Hardness Number

L = Indenter Load in Kilograms

Ap = Unrecovered Projected Area of Indentation

l = Measured Length of the Long Diagonal in Millimeters

Cp = Constant Relating l to the Unrecovered Projected Area

For a perfect Knoop indenter Cp equals 7.028×10^{-2}.

In the present investigation, the Knoop Hardness Number was obtained by multiplying the indenter load, in grams, by a number taken from a chart (14) relating diagonal length to hardness. Also, a correction was made for the imperfection of the Knoop indenter used. (See Calibration of Knoop Indenter - Table II)

APPENDIX B

Calculation of Impurity Concentration

In order to obtain meaningful information from the experiment dealing with the effect of impurity concentration, it was necessary to make an approximation of the impurity concentration within each sample. The resistivity was known. Therefore, if it can be assumed that all current carriers at room temperature are due to impurities, the impurity concentration may be calculated from the expression taken from (13).

$$\frac{1}{\rho} = Ne\mu$$

Where

ρ = Resistivity

N = Concentration of Impurity Atoms

e = Electric Charge on an Electron

μ = Mobility of Charge Carriers

Values for the mobilities of electrons and holes were taken from (13). The mobility of electrons was stated to be 1600 cm^2/volt-sec. and that of holes as 400 cm^2/volt-sec.. After rearrangement, the expression for the concentration of impurity atoms becomes:

$$N = \frac{1}{e}$$

Substitution into this equation gave the listed values.

SAMPLE	RESISTIVITY (ohm-cm)	IMPURITY CONCENTRATION (atoms/cc)
P type		
100D1687S	100.0	10^{14}
100D1732	10.0	10^{15}
6-1424	1.0	10^{16}
100D1777S	0.1	10^{17}
100D1786	0.01	10^{18}
N type		
100D1738S	100.0	10^{14}
102-35S	10.0	10^{15}
100D-1810	1.0	10^{16}
102-85S	0.1	10^{17}
MS2732	0.01	10^{18}
102-30S	0.001	10^{19}

It is stressed that the calculation is intended as an estimate only.

Table I A

Experimental Data

Calibration of Bausch and Lomb Filar Eyepiece with Ten Power Objective

Gage Length		Measured Length	
(mm)	(microns)	(filar units, major)	(filar units, minor)
1.0	1000.0	9.370	937.0
1.0	1000.0	9.365	936.5
1.0	1000.0	9.367	936.7
1.0	1000.0	9.366	936.6
1.0	1000.0	9.361	936.1
1.0	1000.0	9.364	936.4
1.0	1000.0	9.358	935.8
1.0	1000.0	9.365	936.5
1.0	1000.0	9.360	936.0
1.0	1000.0	9.362	936.2
1.0	1000.0	9.364	936.4
		Average Values	
1.0	1000.0	9.363	936.3

1 filar unit, minor = 1.068 microns

Table I B

Experimental Data

Calibration of Bausch and Lomb Filar Eyepiece with Fifty Power Objective

Gage Length		Measured Length	
(mm)	(microns)	(filar units, major)	(filar units, minor)
0.20	200.0	9.854	985.4
0.20	200.0	9.850	985.0
0.20	200.0	9.852	985.2
0.20	200.0	9.852	985.2
0.20	200.0	9.855	985.5
0.20	200.0	9.852	985.2
0.20	200.0	9.849	984.9
0.20	200.0	9.852	985.2
0.20	200.0	9.852	985.2
0.20	200.0	9.854	985.4
		Average Values	
0.20	200.0	9.852	985.2

1 filar unit, minor = 0.203 microns

Table I C

Experimental Data

Calibration of Bausch and Lomb Filar Eyepiece with Ninety Power Objective

Gage Length		Measured Length	
(mm)	(microns)	(filar units, major)	(filar units, minor)
0.080	80.0	8.763	876.3
0.080	80.0	8.762	876.2
0.080	80.0	8.764	876.4
0.080	80.0	8.759	875.9
0.080	80.0	8.762	876.2
0.080	80.0	8.762	876.2
0.080	80.0	8.764	876.4
0.080	80.0	8.760	876.0
0.080	80.0	8.759	875.9
0.080	80.0	8.766	876.6
		Average Values	
0.080	80.0	8.762	876.2

1 filar unit, minor = 0.0913 microns

Table II

Experimental Data

Knoop Indenter Calibration

Length of Indentation (filar units, minor)	(microns)	Hardness (Knoop Number)
478.8	97.2	753.0
468.1	95.0	788.5
467.8	95.0	788.5
466.2	94.6	795.0
475.2	96.5	764.0
476.7	96.7	761.0
473.6	96.1	770.5
470.3	95.5	780.0
473.3	96.1	770.5
478.5	97.2	753.0
474.2	96.3	767.2
472.7	96.0	772.0
471.3	95.7	777.0
475.4	96.5	764.0
476.5	96.7	761.0

Average Hardness - 771.1

Actual Gage Hardness - 759.0

Indenter Correction - -1.6%

Table III

Experimental Data

Preliminary Experiment on the Photomechanical Effect

Without Lamp		With Lamp	
Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
54.0	1185	56.0	1101
52.0	1276	56.0	1101
51.0	1328	56.0	1101
54.0	1185	54.0	1185
58.0	1027	59.6	975
55.0	1140	58.0	1027
53.5	1207	56.0	1101
56.0	1101	57.0	1063
54.0	1185	58.0	1027
Average Hardness		Average Hardness	
1181.5		1076	

Photomechanical Effect

(% softening)

8.9

Table IV

Experimental Data

Hardness Versus Temperature Characteristics

Sample	100D1786
	P type Silicon
	10^{18} impurity atoms per cc
Indenter Load	6 grams
Indenter	Knoop Diamond #KCL-608
Microscope Objective Power	50X
Filar Eyepiece	Bausch and Lomb
Indenter Contact Time	30 seconds
Thermocouple	Chromel-Alumel

All indentations made without radiation

Table IV A

Experimental Data

Temperature 82.5°C

Length of Indentation (filar units, minor)	Hardness (Knoop Number)
48.5	881
41.0	1231
47.5	918
48.5	881
47.5	918
44.0	1070
44.0	1070
44.5	1046
48.5	881
Average Values	
45.1	1040
Standard Deviations	
3.08	1[illegible]3

Table IV B

Experimental Data

Temperature 70.0°C

Length of Indentation (filar units, minor)	Hardness (Knoop Number)
45.5	1002
40.0	1295
45.5	1002
41.0	1231
42.0	1174
41.5	1201
44.0	1070
45.5	1002
43.5	1094
47.5	918
40.5	1264
48.0	899
46.5	957
Average Values	
43.9	1075
Standard Deviations	
2.61	130

Table IV C

Experimental Data

Temperature 60.0°C

Length of Indentation (filar units, minor)	Hardness (Knoop Number)
43.5	1094
44.0	1070
48.0	899
42.5	1147
43.0	1121
42.0	1174
48.0	899
44.5	1046
Average Values	
44.4	1054
Standard Deviations	
2.18	99

Table IV D

Experimental Data

Temperature $50.0^{\circ}C$

Length of Indentation (filar units, minor)	Hardness (Knoop Number)
45.0	1024
41.5	1201
45.5	1002
45.0	1024
44.5	1046
48.5	881
42.0	1174
45.5	1002
48.0	881
48.0	881
Average Values	
45.4	1030
Standard Deviations	
2.26	104

Table IV E

Experimental Data

Temperature 41.0°C

Length of Indentation (filar units, minor)	Hardness (Knoop Number)
43.5	1094
39.0	1362
40.5	1264
47.5	918
47.5	918
41.5	1201
44.0	1070
46.0	980
47.0	937
44.0	1070
Average Values	
44.1	1066
Standard Deviations	
2.85	107

Table IV F

Experimental Data

Temperature 27.0°C

Length of Indentation (filar units, minor)	Hardness (Knoop Number)
46.0	980
41.0	1231
41.5	1201
44.0	1070
47.0	937
43.5	1094
42.5	1147
46.0	980
48.0	899
43.5	1094
Average Values	
44.3	1056
Standard Deviations	
2.26	106

Table V

Experimental Data

Effect of Surface Preparation

Sample	100D1786
	P type Silicon
	10^{18} impurity atoms per cc
Indenter Load	6 grams
Indenter	Knoop Diamond #KCL-608
Microscope Objective Power	50X
Filar Eyepiece	Bausch and Lomb
Indenter Contact Time	30 seconds
Etchants	None
	3 HNO_3 / 1 HCl
	CP-4 (9 HNO_3 / 7 Acetic / 4 HF)

All measurements taken at room temperature

Table V A

Experimental Data

Aged Surface (Unetched) Without Radiation

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
44.5	1046	48.0	899
46.5	957	41.5	1201
45.5	1002	43.5	1094
45.5	1002	44.0	1070
48.5	881	42.5	1147
39.5	1332	43.0	1121
41.5	1201	44.0	1070
43.0	1121	39.5	1332
45.0	1024	43.5	1094
45.0	1024	44.5	1046
46.5	957	44.0	1070
43.5	1094	44.0	1070
43.5	1094	38.5	1398
41.0	1231	41.5	1201
46.5	957	45.0	1024
44.0	1070	42.0	1174
45.5	1002	42.0	1174
48.0	899	42.5	1147

Table V A

Experimental Data

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
49.0	862	43.0	1121
43.0	1121	44.0	1070
44.0	1070	40.5	1264
42.0	1174	43.5	1094
47.0	937	45.0	1024

Average Values

Length of Indentation	Hardness
43.75	1082.4

Standard Deviations

2.21	113.5

Table V B

Experimental Data

Aged Surface (Unetched) With Radiation

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
41.0	1231	45.0	1024
44.5	1046	48.0	899
46.0	980	46.0	980
56.0	662	48.5	881
46.5	957	45.5	1002
44.5	1046	46.0	980
42.5	1147	43.0	1121
44.0	1070	45.0	1024
46.5	957	48.0	899
46.5	957	47.0	937
48.0	899	49.0	862
45.5	1002	57.0	639
44.0	1174	43.0	1121
44.5	1046	43.0	1121
46.5	957	46.5	957
45.5	1002	42.0	1174
45.5	1002	44.0	1070
44.0	1070	47.5	918

Table V B

Experimental Data

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
44.0	1070	49.0	862
43.5	1094	44.5	1046
48.5	881	47.0	937
52.5	752	49.5	845
41.5	1201	45.5	1002
52.0	766		

Average Values

Length of Indentation	Hardness
46.16	972

Standard Deviations

3.15	123

Table V C

Experimental Data

Freshly Etched in 3 HNO_3 / 1 HCl   Without Radiation

Length of Indentation (filar units, minor)	Hardness (Knoop Number	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
43.0	1121	48.5	881
44.0	1070	41.5	1201
44.5	1046	46.5	957
42.5	1147	48.0	899
41.0	1231	44.0	1070
41.5	1201	47.0	937
42.0	1174	43.0	1121
39.0	1362	44.5	1046
42.5	1147	45.5	1002
47.5	918	43.5	1094
43.0	1121	41.5	1201
42.0	1174	41.0	1231
39.5	1332	47.0	937
44.0	1070	40.5	1264
42.5	1147	39.0	1362
40.5	1264	47.5	918
41.0	1231	47.5	918

Table V C

Experimental Data

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
38.5	1398	42.0	1174
41.0	1231	44.0	1070
45.5	1002	48.5	881
43.0	1121	48.0	899
39.0	1362	42.5	1147

Average Values

Length of Indentation	Hardness
43.3	1108

Standard Deviations

2.80	133

Table V D

Experimental Data

Freshly Etched in 3 HNO_3 / 1 HCl   With Radiation

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
44.5	1046	46.5	957
48.5	881	46.0	980
51.0	797	48.0	899
46.0	980	45.5	1002
52.5	752	44.0	1070
51.5	782	44.0	1070
49.0	862	49.5	845
47.0	937	54.0	712
46.5	957	41.5	1201
44.0	1070	49.5	845
43.0	1121	43.0	1121
45.5	1002	47.0	937
45.0	1024	44.5	1046
50.0	829	46.0	980
45.5	1002	47.0	937
46.5	980	41.5	1201
44.5	1046	45.5	1002

Table V D

Experimental Data

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
50.0	829	45.5	1002
47.0	937	51.5	782
44.5	1046	43.0	1121
43.5	1094	55.5	674
44.5	1046	40.5	1264
44.5	1046	55.0	686
44.5	1046	49.0	862
47.0	937	46.0	980
41.0	1231	47.5	918
47.5	918	47.0	937
44.0	1070	47.0	937
43.5	1094	40.0	1295
54.0	712	47.0	937
47.0	937		

Average Values

Length of Indentation	Hardness
46.5	957

Standard Deviations

2.41	137

Table V E

Experimental Data

Freshly Etched in CP-4 Without Radiation

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
47.5	918	47.0	937
48.0	899	49.5	845
50.0	829	47.0	937
52.0	766	47.0	937
50.5	812	45.0	1024
47.5	918	45.0	1024
51.0	797	48.0	899
49.0	862	53.5	725
48.0	899	45.0	1024
53.5	725	46.0	980
48.5	881	48.0	980
53.5	725	45.5	1002
49.0	862	44.0	1070
53.0	738	41.0	1231
46.5	957	43.0	1121
49.5	845	50.5	812
40.0	1295	46.5	957

Table V E

Experimental Data

Average Values

Length of Indentation	Hardness
48.0	899
Standard Deviations	
3.49	145

Table V F

Experimental Data

Freshly Etched in CP-4 With Radiation

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
53.0	738	55.5	674
50.5	812	53.5	725
55.0	686	53.0	738
61.5	548	57.5	625
59.5	588	57.0	637
58.0	616	55.0	686
53.5	725	48.0	899
54.5	699	45.0	1024
62.0	539	45.5	1002
57.0	637	47.0	937
55.0	686	54.5	699
42.0	1174	53.5	725
63.0	522	55.0	686
54.5	699	66.5	468
50.5	812	57.5	625
47.5	918	55.5	674
64.5	498	51.5	782
50.0	829	52.5	752

Table V F

Experimental Data

Average Values

Length of Indentation	Hardness
54.2	706
Standard Deviations	
4.95	151

Table V G

Experimental Data

Surface Relaxation

Without Radiation		With Radiation	
Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
54.5	699	67.0	461
51.0	797	60.5	566
51.5	782	57.5	625
56.0	662	59.0	595
55.0	686	60.0	576
54.0	712	57.0	637
48.5	881	55.5	674
48.5	881	62.0	539
49.5	845	54.0	712
51.0	797	57.5	625
53.0	738	58.0	616
56.0	662	59.5	588
49.5	845	60.0	576
Average Values			
51.9	767	59.0	594
Standard Deviations			
2.68	78.5	3.08	59.8

Table VI

Experimental Data

Hardness Versus Temperature Characteristics

With and Without Radiation

Sample	100D1786
	P type Silicon
	10^{18} impurity atoms per cc
Indenter Load	6 grams
Indenter	Knoop Diamond #KCL-608
Microscope Objective Power	50X
Filar Eyepiece	Bausch and Lomb
Indenter Contact Time	30 seconds
Thermocouple	Chromel-Alumel

Table VI A

Experimental Data

Without Radiation

Temperature $80^{\circ}C$

Length of Indentation (filar units, minor)	Hardness (Knoop Number)
49.0	862
55.0	686
54.0	712
50.0	829
56.5	649
59.5	588
53.5	725
49.5	845
57.0	637
56.0	662
53.5	725
54.0	712
Average Values	
54.0	712
Standard Deviations	
3.06	83

Table VI B

Experimental Data

With Radiation

Temperature 75°C

Length of Indentation (filar units, minor)	Hardness (Knoop Number)
57.5	625
53.5	725
53.5	725
54.5	699
51.0	797
55.0	686
58.5	606
55.5	674
58.0	616
54.0	712
51.0	797
Average Values	
54.7	706
Standard Deviations	
2.42	63

Table VI C

Experimental Data

Without Radiation

Temperature 69.5°C

Length of Indentation (filar units, minor)	Hardness (Knoop Number)
58.5	606
49.0	862
55.5	674
55.5	674
48.5	881
49.5	845
51.5	782
54.5	699
56.5	649
Average Values	
53.2	732
Standard Deviations	
3.46	97

Table VI D

Experimental Data

With Radiation

Temperature 65°C

Length of Indentation (filar units, minor)	Hardness (Knoop Number)
52.0	766
57.5	625
56.5	649
51.0	797
53.0	738
59.0	595
58.5	606
52.0	766
55.0	686
54.0	712
53.5	725
Average Values	
54.7	706
Standard Deviations	
2.63	67

Table VI E

Experimental Data

Without Radiation

Temperature $60^{\circ}C$

Length of Indentation (filar units, minor)	Hardness (Knoop Number)
53.5	725
51.5	782
55.0	686
53.0	738
51.5	782
Average Values	
52.9	734
Standard Deviations	
1.32	37

Table VI F

Experimental Data

With Radiation

Temperature $57^{\circ}C$

Length of Indentation (filar units, minor)	Hardness (Knoop Number)
54.0	712
49.5	834
51.0	797
53.5	725
54.5	699
57.0	637
56.0	662
52.0	766
54.5	799
49.5	845
58.5	606
Average Values	
53.6	720
Standard Deviations	
2.82	76

Table VI G

Experimental Data

Without Radiation

Temperature $51^{\circ}C$

Length of Indentation (filar units, minor)	Hardness (Knoop Number)
52.0	766
52.0	766
53.0	638
51.5	782
50.5	812
51.5	782
52.0	766
51.0	797
51.0	797
56.0	662
Average Values	
52.0	766
Standard Deviations	
1.47	40

Table VI H

Experimental Data

With Radiation

Temperature 49°C

Length of Indentation (filar units, minor)	Hardness (Knoop Number)
57.0	637
55.5	674
58.0	616
50.5	812
54.5	799
54.0	712
58.5	606
51.0	797
54.0	712
57.0	637
49.0	862
Average Values	
54.4	702
Standard Deviations	
3.10	81

Table VI I

Experimental Data

Without Radiation

Temperature 40°C

Length of Indentation (filar units, minor)	Hardness (Knoop Number)
51.5	782
54.5	699
53.5	725
52.0	766
50.0	829
49.5	845
49.5	845
55.0	686
Average Values	
51.9	768
Standard Deviations	
2.07	60

Table VI J

Experimental Data

With Radiation

Temperature 39°C

Length of Indentation (filar units, minor)	Hardness (Knoop Number)
54.0	712
50.5	812
56.5	649
55.5	674
52.5	752
54.0	712
54.5	699
59.0	595
55.5	674
Average Values	
54.6	695
Standard Deviations	
2.28	58

Table VI K

Experimental Data

Without Radiation

Temperature 29.5°C

Length of Indentation (filar units, minor)	Hardness (Knoop Number)
54.0	712
52.0	766
54.0	712
49.5	845
48.0	899
51.0	797
52.5	752
53.0	738
51.0	797
47.0	937
Average Values	
51.3	787
Standard Deviations	
2.30	73

Table VI L

Experimental Data

With Radiation

Temperature 29.5°C

Length of Indentation (filar units, minor)	Hardness (Knoop Number)
57.0	637
55.5	674
58.5	606
54.5	699
59.0	595
54.0	712
53.0	738
54.0	712
54.0	712
59.5	588
54.5	699
54.5	699
Average Values	
55.7	666
2.14	50

Table VII

Experimental Data

Effect of Impurity Concentration on the Photomechanical Effect

Samples	P Type Silicon
	100D1786 - 10^{18} impur. atoms/cc
	100D1777S - 10^{17} impur. atoms/cc
	6-1424 - 10^{16} impur. atoms/cc
	100D1732 - 10^{15} impur. atoms/cc
	100D1687S - 10^{14} impur. atoms/cc
	N Type Silicon
	102-30S - 10^{19} impur. atoms/cc
	MS2732 - 10^{18} impur. atoms/cc
	102-85S - 10^{17} impur. atoms/cc
	100D1810 - 10^{16} impur. atoms/cc
	102-35S - 10^{15} impur. atoms/cc
	100D1738S - 10^{14} impur. atoms/cc
Indenter Load	6 grams
Indenter	Knoop Diamond #KCL-608
Microscope Objective Power	50 X
Filar Eyepiece	Bausch and Lomb
Indenter Contact Time	30 seconds

All readings taken at room temperature

Table VII A

Experimental Data

With Radiation

Sample 100D1687S

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
52.0	766	53.0	738
53.0	738	52.5	752
51.5	682	49.0	862
52.5	752	47.5	918
49.0	862	55.0	686
50.0	829	50.0	829
52.0	766	52.0	766
49.0	862	52.0	766
53.5	725	50.0	829
48.0	899	49.5	845
54.0	712	57.0	637

Length of Indentation	Hardness
Average Values	
51.4	785
Standard Deviations	
2.32	67

Photomechanical Effect

(% softening)

17.3

Table VII B

Experimental Data

Without Radiation

Sample 100D1687S

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
47.5	918	48.0	899
45.0	1024	47.0	937
46.5	957	48.5	881
43.0	1121	48.0	899
47.0	937	48.0	899
46.0	980	46.5	957
48.5	881	50.5	812
43.0	1121	47.0	937
48.0	899	50.5	812
47.0	937	48.0	899
47.5	918	44.0	1070

Length of Indentation	Hardness
Average Values	
46.6	953
Standard Deviations	
1.96	67

Table VII C

Experimental Data

With Radiation

Sample 100D1732

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
50.5	812	54.0	712
52.5	752	52.5	752
48.5	881	52.5	752
49.0	862	50.0	829
49.5	845	49.5	845
52.5	752	56.0	662
50.0	829	48.0	899
51.5	782	47.5	918
49.5	845	52.0	766
52.0	766	53.5	725

Length of Indentation	Hardness
Average Values	
51.0	797
Standard Deviations	
2.14	64

Photomechanical Effect

(% softening)

9.1

Table VII D

Experimental Data

Without Radiation

Sample 100D1732

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
47.0	937	48.0	899
49.0	862	52.0	766
48.5	881	44.5	1046
50.5	812	47.5	918
45.0	1024	44.0	1070
49.5	845	52.0	766
47.0	937	53.5	725
47.5	918	51.0	797
51.5	782	44.5	1046
53.5	725	45.5	1002
		50.0	829

Length of Indentation	Hardness
Average Values	
48.6	877
Standard Deviations	
2.90	96

Table VII E

Experimental Data

With Radiation

Sample 6-1424

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
53.0	738	55.5	674
50.0	829	55.0	686
51.0	797	56.0	738
56.0	662	53.0	625
51.5	782	57.5	625
50.5	812	57.5	625
59.0	595	49.0	862
55.0	686	49.0	862
52.5	752	52.0	766
56.0	662	55.0	686

	Length of Indentation	Hardness
Average Values	53.9	715
Standard Deviations	2.83	77

Photomechanical Effect

(% softening)

8.9

Table VII F

Experimental Data

Without Radiation

Sample 6-1424

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
51.0	797	50.0	829
51.5	782	49.5	845
50.0	829	54.5	699
49.0	862	51.0	797
53.0	738	53.5	725
51.5	782	50.0	829
53.5	725	50.0	829
50.0	829	53.5	725
49.5	845	51.5	782
52.0	766	51.5	782
53.0	738	49.0	862
50.0	829	53.0	739
		55.0	686

Length of Indentation	Hardness
Average Values	
51.4	785
Standard Deviations	
1.73	36

Table VII G

Experimental Data

With Radiation

Sample 100D1777S

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
52.0	766	52.0	766
50.5	812	51.5	782
44.5	1046	48.5	881
51.5	782	53.5	725
49.5	845	53.5	725
48.5	881	49.0	862
50.0	829	53.5	725
55.0	829	45.5	1002
53.5	725	50.0	829
51.0	797	52.0	766
47.0	937	49.0	862

Length of Indentation	Hardness
Average Values	
50.2	822
Standard Deviations	
3.22	110

Photomechanical Effect

(% softening)

12.8

Table VII H

Experimental Data

Without Radiation

Sample 100D1777S

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
50.5	812	45.0	1024
43.5	1094	45.5	1002
44.5	1046	50.5	812
50.0	829	48.5	881
46.0	980	46.5	957
44.5	1046	48.0	899
44.0	1070	47.5	918
49.0	862	49.0	862
42.0	1174	50.5	812
44.5	1046	44.5	1064
50.0	829	48.0	899
55.0	686	47.0	937
46.5	957	44.5	1046

Length of Indentation	Hardness
Average Values	
46.9	941
Standard Deviations	
2.82	109

Table VII I

Experimental Data

With Radiation

Sample 100D1786

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
49.5	845	53.0	738
52.0	766	48.5	881
52.5	752	50.5	812
53.5	725	48.0	899
54.0	712	55.5	674
52.5	752	55.0	686
54.5	699	47.5	899
50.0	829	50.5	812
48.5	881	50.0	829
49.5	845	53.0	738
53.0	738	51.5	782

Length of Indentation	Hardness
Average Values	
51.8	771
Standard Deviations	
2.25	72

Photomechanical Effect

(% softening)

10.2

Table VII J

Experimental Data

Without Radiation

Sample 100D1786

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
47.5	918	49.5	845
48.5	881	50.5	812
52.0	766	51.0	797
48.0	899	49.0	862
53.0	738	46.5	957
52.0	766	45.0	1024
47.0	937	50.5	812
48.0	899	52.5	752
46.5	957	46.0	980
46.0	980	46.5	957
49.0	862	47.0	937
48.0	899		

Length of Indentation	Hardness
Average Values	
49.2	859
Standard Deviations	
2.19	81

Table VII K

Experimental Data

With Radiation

Sample 100D1738S

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
56.0	662	49.0	862
57.0	637	51.0	797
53.5	725	50.5	812
49.5	845	48.5	881
52.0	766	49.5	845
47.5	918	49.5	845
50.0	829	49.0	862
53.0	738	50.5	812
53.0	738	47.0	937
53.0	738	48.5	881
50.0	829	48.0	899

Length of Indentation	Hardness
Average Values	
50.9	800
Standard Deviations	
2.10	81

Photomechanical Effect

(% softening)

12.5

Table VII L

Experimental Data

Without Radiation

Sample 100D1738S

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
47.5	918	50.0	829
50.0	829	49.5	845
49.5	845	46.0	980
49.0	862	49.0	862
47.5	918	45.5	1002
49.0	862	46.5	957
48.0	899	45.0	1024
45.5	1002	48.5	881
48.0	899	49.5	845
48.0	899	45.0	1024
		44.5	1046

Length of Indentation	Hardness
Average Values	
47.6	914
Standard Deviations	
1.77	71

Table VII M

Experimental Data

With Radiation

Sample 102-35S

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
56.0	662	50.5	812
50.5	812	49.0	862
51.5	782	52.5	752
48.5	881	47.0	937
48.0	899	51.5	782
47.0	937	49.5	845
50.5	812	51.5	782
48.5	881	51.0	797
52.5	752	51.5	782
51.5	782	46.0	980
53.0	738		

Length of Indentation	Hardness
Average Values	
50.3	819
Standard Deviations	
2.22	72

Photomechanical Effect

(% softening)

13.7

Table VII N

Experimental Data

Without Radiation

Sample 102-35S

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
44.5	1046	46.0	980
46.0	980	47.0	937
42.5	1147	46.5	957
48.5	881	46.0	980
49.0	962	46.0	980
49.5	845	47.0	937
46.5	957	44.5	1046
47.0	937	49.0	862
49.5	845	46.0	980
46.0	980	45.5	1002
48.0	899		

	Length of Indentation	Hardness
Average Values	46.7	949
Standard Deviations	1.75	73

Table VII O

Experimental Data

With Radiation

Sample 100D1810

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
50.0	829	49.5	845
49.0	862	49.0	862
49.5	845	49.0	862
51.0	797	53.0	738
48.5	881	49.5	845
49.5	845	49.0	862
49.0	862	50.0	829
54.0	712	48.5	881
54.0	712	51.5	782
49.5	845	50.0	829
52.5	752	52.0	766

Length of Indentation	Hardness
Average Values	
50.5	812
Standard Deviations	
2.03	60

Photomechanical Effect

(% softening)

13.7

Table VII P

Experimental Data

Without Radiation

Sample 100D1810

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
49.0	862	48.5	881
45.0	1024	46.5	957
46.5	957	47.5	918
52.5	752	45.5	1002
50.0	829	45.5	1002
47.0	937	51.5	782
49.5	845	47.0	937
52.0	766	42.0	1121
45.0	1024	44.0	1070
45.0	1024	44.5	1046
47.5	918	44.5	1046
45.0	1024	43.0	1121

	Length of Indentation	Hardness
Average Values	46.9	941
Standard Deviations	2.67	104

Table VII Q

Experimental Data

With Radiation

Sample 102-85S

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
47.0	937	53.5	725
50.0	829	51.0	797
49.5	845	48.5	881
49.5	845	54.0	712
49.0	862	52.5	752
51.0	797	50.0	829
47.0	937	54.0	712
52.0	766	47.5	918
52.5	752	47.5	918
50.0	752	53.5	725
51.5	782		

Length of Indentation	Hardness
Average Values	
50.5	812
Standard Deviations	
2.15	68

Photomechanical Effect

(% softening)

12.0

Table VII R

Experimental Data

Without Radiation

Sample 102-85S

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
50.0	829	45.5	1002
46.0	980	47.0	937
48.0	899	45.5	1002
46.0	980	43.5	1094
48.0	899	49.0	862
48.5	881	47.0	937
47.0	937	51.0	797
43.0	1121	50.0	829
51.5	782	47.5	918
43.5	1094	52.0	766
42.5	1147	50.0	829
51.0	797	46.5	957
		44.5	1046

Length of Indentation	Hardness
Average Values	
47.4	922
Standard Deviations	
2.71	108

Table VII S

Experimental Data

With Radiation

Sample MS2732

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
53.5	725	48.0	899
49.0	862	54.0	712
47.5	918	52.5	752
50.5	812	50.5	812
53.0	738	53.5	725
48.0	899	57.5	625
47.0	937	50.0	829
52.0	766	53.0	738
50.5	812	46.5	957
48.0	899	48.0	899
49.0	862	51.0	797

	Length of Indentation	Hardness
Average Values	50.6	809
Standard Deviations	2.74	87

Photomechanical Effect

(% softening)

15.2

Table VII T

Experimental Data

Without Radiation

Sample MS2732

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
50.0	829	44.0	1070
48.5	881	51.0	797
47.0	937	45.5	1002
47.5	918	47.0	937
45.5	1002	43.5	1094
50.0	829	48.0	899
44.0	1070	45.0	1024
46.0	980	45.5	1002
41.0	1231	48.5	881
51.0	797	47.5	918
46.5	957	43.0	1121
47.0	937	44.0	1070
49.0	962	45.5	1002

	Length of Indentation	Hardness
Average Values	46.6	953
Standard Deviations	2.03	60

Table VII U

Experimental Data

With Radiation

Sample 102-30S

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
46.0	980	55.5	674
49.0	862	53.5	725
53.0	738	53.5	725
53.5	725	52.0	766
50.5	812	55.5	674
49.0	862	51.5	782
53.0	738	48.0	899
52.5	752	51.0	797
50.0	829	52.5	752
50.5	812	52.5	752
50.0	829	51.0	797

Length of Indentation	Hardness
Average Values	
51.5	782
Standard Deviations	
2.13	58

Photomechanical Effect

(% softening)

12.0

Table VII V

Experimental Data

Without Radiation

Sample 102-30S

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
49.0	862	47.0	937
46.5	957	51.0	797
45.5	1002	48.0	899
51.5	782	53.5	725
50.0	829	51.0	797
50.5	812	48.5	881
51.5	782	49.5	845
46.5	957	53.0	738
50.0	829	47.5	918
48.5	881	49.0	862
49.5	845	47.0	937
52.5	752	49.5	845
47.0	937	48.0	899

Length of Indentation	Hardness
Average Values	
48.3	888
Standard Deviations	
2.55	79

Table VIII

Experimental Data

Relation of Indenter Load to the Photomechanical Effect

Sample	100D1687S
	P type Silicon
	10^{14} impurity atoms per cc
Indenter	Knoop Diamond #KCL-608
Filar Eyepiece	Bausch and Lomb
Indenter Contact Time	30 seconds

All readings taken at room temperature

Table VIII A

Experimental Data

Without Radiation

Indenter Load 1 gram

Microscope Objective Power 90 X

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
57.5	516	51.5	644
53.5	592	49.5	696
53.0	607	49.0	728
51.0	660	55.0	565
56.0	543	50.0	693
48.5	724	52.0	634
54.5	572	50.0	693
55.5	551	53.0	607
		53.5	592

Length of Indentation	Hardness
Average Values	
52.5	620
Standard Deviations	
2.56	64

Photomechanical Effect

(% softening)

5.5

Table VIII B

Experimental Data

With Radiation

Indenter Load 1 gram

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
49.5	696	59.0	488
50.5	677	59.0	488
52.0	631	56.5	535
56.5	535	51.5	644
52.5	619	51.0	660
54.5	572	50.5	677
51.5	644	56.0	543
56.0	543	55.5	551
51.0	660	51.0	660
		52.5	619

Length of Indentation	Hardness
Average Values	
54.0	586
Standard Deviations	
3.21	72

Table VIII C

Experimental Data

Without Radiation

Indenter Load	2 grams
Microscope Objective Power	90 X

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
73.5	634	61.0	907
64.0	822	59.0	958
64.5	818	65.5	790
73.5	634	60.0	941
60.0	941	59.0	977
58.0	1013	62.5	876
63.5	846	58.5	994
63.0	860	63.5	846
		63.5	846

Length of Indentation	Hardness
Average Values	
63.0	861
Standard Deviations	
4.24	120

Photomechanical Effect

(% softening)

8.4

Table VIII D

Experimental Data

With Radiation

Indenter Load 2 grams

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
70.0	694	67.5	740
77.5	564	71.5	642
70.0	694	68.5	728
64.5	818	72.5	653
66.0	790	71.5	642
66.5	764	70.5	685
78.5	549		

	Length of Indentation	Hardness
Average Values	70.4	689
Standard Deviations	3.82	75

Table VIII E

Experimental Data

Without Radiation

Indenter Load 3 grams

Microscope Objective Power 50 X

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
39.0	684	38.0	720
39.5	666	36.0	801
35.5	822	36.5	780
31.0	1074	37.0	759
36.0	801	37.0	759
36.5	780	40.5	636

Length of Indentation	Hardness
Average Values	
36.9	761
Standard Deviations	
1.70	104

Photomechanical Effect

(% softening)

11.5

Table VIII F

Experimental Data

With Radiation

Indenter Load 3 grams

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
36.5	780	37.5	738
38.5	702	38.0	720
37.5	738	40.5	630
35.5	822	37.5	738
38.0	720	44.5	528
40.0	648	42.0	591
38.5	702	40.0	648
38.5	702	35.5	822
39.5	666	39.5	666
43.5	552		

Length of Indentation	Hardness
Average Values	
39.2	674
Standard Deviations	
2.32	73

Table VIII G

Experimental Data

Without Radiation

Indenter Load 4 grams

Microscope Objective Power 50 X

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar Units, minor)	Hardness (Knoop Number)
39.0	912	32.0	1348
39.0	912	39.0	912
37.5	982	32.0	1348
33.0	1268	37.5	984
32.5	1308	34.0	1196
32.0	1344	39.5	888
31.5	1388	38.0	960
39.0	912	36.5	1040
37.5	984	36.5	1040

Length of Indentation	Hardness
Average Values	
35.7	973
Standard Deviations	
2.79	211

Photomechanical Effect

(% softening)

12.5

Table VIII H

Experimental Data

With Radiation

Indenter Load 4 grams

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
40.5	848	39.0	912
46.5	632	41.0	824
41.0	824	38.5	936
40.5	848	38.0	960
41.5	808	42.5	752
38.5	936	38.5	936
37.0	1012	40.5	848

Length of Indentation	Hardness
Average Values	
40.2	853
Standard Deviations	
2.29	94

Table VIII I

Experimental Data

Without Radiation

Indenter Load 5 grams

Microscope Objective Power 50 X

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
46.0	815	44.5	880
39.5	1110	46.5	795
43.0	940	40.5	1060
43.0	940	43.0	940
41.0	1030	44.5	880
41.5	1010	41.0	1030
44.0	900	40.0	1085
39.0	1140	48.0	750
39.5	1110	40.0	1085

Length of Indentation	Hardness
Average Values	
42.5	1066
Standard Deviations	
2.47	150

Photomechanical Effect

(% softening)

22.1

Table VIII J

Experimental Data

With Radiation

Indenter Load 5 grams

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
49.5	710	45.0	858
49.0	720	47.5	766
44.5	880	46.5	795
42.0	985	44.0	900
47.5	766	45.0	858
46.0	815	44.0	900
48.0	750	47.5	766
45.0	860	42.5	962
43.5	920	43.5	920
47.0	782	44.0	900

Length of Indentation	Hardness
Average Values	
45.6	830
Standard Deviations	
2.04	78

Table VIII K

Experimental Data

Without Radiation

Indenter Load 6 grams

Microscope Objective Power 50 X

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
53.0	738	53.0	738
52.5	752	49.0	862
49.0	862	55.0	686
50.0	829	47.5	918
52.0	766	50.0	829
49.0	862	52.0	766
53.5	725	50.0	829
48.0	899	49.5	845
54.0	712	57.0	637

Length of Indentation	Hardness
Average Values	
51.4	785
Standard Deviations	
2.32	67

Photomechanical Effect

(% softening)

17.3

Table VIII L

Experimental Data

With Radiation

Indenter Load 6 grams

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
47.5	918	48.0	899
45.0	1024	47.0	937
46.5	957	48.5	881
43.0	1121	48.0	899
47.0	937	48.0	899
46.0	980	46.5	957
48.5	881	50.5	812
43.0	1121	47.0	937
48.0	899	50.5	812
47.0	937	48.0	899
47.5	918	47.0	937
44.0	1070		

Length of Indentation	Hardness
Average Values	
46.6	953
Standard Deviations	
1.96	67

Table VIII M

Experimental Data

Without Radiation

Indenter Load 8 grams

Microscope Objective Power 50 X

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
54.0	944	53.0	984
53.5	960	52.5	1000
58.0	816	57.0	848
53.5	960	53.0	984
51.5	1048	50.0	1104
56.0	880	56.0	880
55.0	912	56.0	880
51.5	1048	54.5	928

Length of Indentation	Hardness
Average Values	
53.7	958
Standard Deviations	
2.29	82

Photomechanical Effect

(% softening)

12.8

Table VIII N

Experimental Data

With Radiation

Indenter Load 8 grams

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
54.5	928	59.0	790
54.5	928	56.0	880
60.0	765	59.5	778
58.0	816	55.0	912
57.0	848	60.5	753
60.0	765	57.0	848
56.5	864	59.5	778
59.5	778	55.0	912
53.5	960	60.0	765

	Length of Indentation	Hardness
Average Values	57.5	835
Standard Deviations	2.28	66

Table VIII O

Experimental Data

Without Radiation

Indenter Load 10 grams

Microscope Objective Power 50 X

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
60.0	956	62.5	882
63.5	855	59.5	972
59.5	972	60.5	941
62.5	882	62.5	882
61.5	911	65.5	804
60.0	956	64.5	829
61.5	911	61.5	911
64.0	842	63.5	855

Length of Indentation	Hardness
Average Values	
61.4	917
Standard Deviations	
1.86	54

Photomechanical Effect

(% softening)

8.3

Table VIII P

Experimental Data

With Radiation

Indenter Load 10 grams

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
67.0	769	65.0	816
65.0	816	60.5	941
63.5	855	67.5	758
63.5	855	65.5	804
67.5	758	62.0	896
68.5	736	63.5	855
64.0	842	68.0	747
66.0	792	59.5	972
59.5	972	59.5	972
62.5	882	62.0	896

Length of Indentation	Hardness
Average Values	
64.0	842
Standard Deviations	
2.38	72

Table VIII Q

Experimental Data

Without Radiation

Indenter Load 13 grams

Microscope Objective Power 50 X

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
74.0	822	71.5	880
67.0	1000	67.5	985
70.0	918	72.0	868
70.0	918	68.5	985
67.0	1000	66.5	1015
73.5	833	68.5	957
74.5	811	67.5	985
74.0	822	68.5	957
76.0	780	71.5	880

Length of Indentation	Hardness
Average Values	
70.5	904
Standard Deviations	
2.76	69

Photomechanical Effect

(% softening)

4.4

Table VIII R

Experimental Data

With Radiation

Indenter Load 13 grams

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
69.0	944	72.5	857
75.5	790	69.0	944
73.0	844	73.0	844
77.0	755	71.0	893
69.5	931	78.0	737
73.0	845	73.5	933
69.5	931	70.0	918
70.0	918	72.5	931
74.5	811	69.5	931
71.0	893		

Length of Indentation	Hardness
Average Values	
72.1	863
Standard Deviations	
2.64	53

Table IX

Experimental Data

Crystallographic Effects on the Photomechanical Effect

Sample	100D1687S
	P type Silicon
	10^{14} impurity atoms per cc
Indenter Load	6 grams
Indenter	Knoop Diamond #KCL-608
Microscope Objective Power	50 X
Filar Eyepiece	Bausch and Lomb
Indenter Contact Time	30 seconds

Angles are arbitrarily taken with 0° being along the long edge of the sample

All readings were taken at room temperature

Table IX A

Experimental Data

Angle 0°

With Radiation

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
52.5	752	57.0	637
52.5	752	51.5	782
55.5	686	51.5	782
54.0	712	48.0	899
48.0	899	52.5	752
48.0	899	52.0	766
55.5	686	49.5	845
53.5	725	48.5	881
56.0	662	50.5	812
51.5	782	51.0	797
55.5	686	54.5	699

Length of Indentation	Hardness
Average Values	
52.0	766

Photomechanical Effect

(% softening)

14.5

Table IX B

Experimental Data

Angle 0°

Without Radiation

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
47.5	918	50.5	812
47.5	918	47.5	918
46.0	980	50.5	812
50.0	829	42.0	1174
49.5	845	44.0	1070
47.5	918	53.0	738
54.5	699	46.5	957
47.5	918	49.0	862
50.0	829	44.5	1046
48.0	899	48.0	899
48.5	881		

Length of Indentation	Hardness
Average Values	
48.2	895

Table IX C

Experimental Data

Angle 30°

With Radiation

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
50.0	829	46.5	957
47.0	937	52.0	766
49.0	862	56.5	649
52.5	752	50.5	812
48.0	899	53.0	738
47.5	918	53.0	738
47.5	918	48.0	899
52.0	766	48.0	899
53.5	725	54.0	712
54.5	699	50.5	812
54.0	712	47.5	918
53.5	725	50.5	812

Length of Indentation	Hardness
Average Values	
50.8	805

Photomechanical Effect

(% softening)

17.5

Table IX D

Experimental Data

Angle 30°

Without Radiation

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
47.0	937	48.0	899
46.5	957	43.5	1094
47.5	918	45.0	1024
44.0	1070	44.5	1046
44.5	1046	46.5	1046
48.0	899	48.0	899
46.0	980	52.0	766
47.5	918	43.5	1094
44.5	1046	47.0	937
50.5	812	43.0	1121
43.5	1094	43.0	1121
40.5	881	48.0	899

Length of Indentation	Hardness
Average Values	
46.2	974

Table IX E

Experimental Data

Angle 60°

With Radiation

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
51.5	782	49.0	862
55.0	686	54.5	699
51.5	782	53.5	725
53.0	738	57.0	637
54.0	712	53.0	738
55.5	674	54.0	712
58.0	616	54.0	712
50.5	766	52.0	766
49.5	845	52.5	752
50.0	829	52.5	752
50.0	829	57.0	637
55.5	674	56.5	649

Length of Indentation	Hardness
Average Values	
54.1	708

Photomechanical Effect

(% softening)

21.1

Table IX F

Experimental Data

Angle 60°

Without Radiation

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
51.0	797	44.0	1070
47.5	918	49.5	845
48.5	881	50.5	812
46.5	957	49.0	862
46.5	957	49.0	862
51.0	797	45.5	1002
51.0	797	46.5	957
52.5	752	42.5	1147
41.5	1201	52.0	766
46.5	957	52.0	766
49.5	845		

Length of Indentation	Hardness
Average Values	
48.0	899

Table IX G

Experimental Data

Angle 90°

With Radiation

Length of Indentation (filar units, minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
57.0	637	53.5	725
50.5	812	52.0	766
53.0	738	49.5	845
53.0	738	60.0	576
55.0	686	51.0	797
51.5	782	53.0	738
56.0	662	51.0	797
51.0	797	53.5	725
50.0	829	55.0	686
53.5	725	56.5	649
55.0	686	50.5	812
52.0	766		

Length of Indentation	Hardness
Average Values	
53.0	738

Photomechanical Effect

(% softening)

13.7

Table IX H

Experimental Data

Angle 90°

Without Radiation

Length of Indentation (filar units minor)	Hardness (Knoop Number)	Length of Indentation (filar units, minor)	Hardness (Knoop Number)
46.5	957	49.0	862
48.5	881	53.0	738
50.5	812	51.0	797
50.5	812	51.5	782
47.5	918	46.0	980
47.5	918	43.5	1094
49.5	845	52.5	752
54.5	699	49.0	862
48.0	899	51.0	797
47.5	918	47.5	918

Length of Indentation	Hardness
Average Values	
49.2	856

Table X

Experimental Data

Effect of Infrared Wavelengths

Sample	100D1687S
	P type Silicon
	10^{14} impurity atoms per cc
Indenter Load	6 grams
Indenter	Knoop Diamond #KCL-608
Microscope Objective Power	50 X
Filar Eyepiece	Bausch and Lomb
Indenter Contact Time	30 seconds

All readings taken at room temperature

Table X A

Experimental Data

Without Radiation

Length of Indentation (filar units, minor)	Hardness (Knoop Number)
46.5	957
46.0	980
50.0	829
49.5	845
47.0	937
48.5	881
47.5	918
47.0	937
46.5	957
49.0	862
47.0	937
46.5	957
47.5	918
47.0	937
Average Values	
47.6	914
Standard Deviations	
1.15	39

Table X B

Experimental Data

With Radiation

Length of Indentation (filar units, minor)	Hardness (Knoop Number)
51.5	782
52.0	766
51.5	782
50.0	829
50.5	812
51.0	797
52.0	766
50.0	829
51.0	797
51.5	782
52.5	752
53.0	738
50.0	829
51.5	782
51.0	797
Average Values	
51.3	788
Standard Deviations	
.91	29

Table X C

Experimental Data

With Filtered Radiation

Length of Indentation (filar units, minor)	Hardness (Knoop Number)
51.0	797
48.0	899
48.0	899
47.5	918
45.0	937
46.0	881
47.0	980
46.5	957
48.5	881
49.0	862
47.5	918
47.0	937
48.5	881
46.0	980
47.0	937
Average Values	
47.5	918
Standard Deviations	
1.41	53

115225